An Environmental Life Cycle Assessment of Energy Systems Leading to a Pathway for a Low Carbon Economy

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ABSTRACT

In 2008, the UK Government enforced the target to reduce the UK carbon account for the year 2050 to at least 80% less than the 1990 baseline. In order to meet this ambitious target it is widely thought that the UK energy future should be 'electrified' as a suite of low carbon generation technologies provide ever increasing proportions of electricity supply.

This work has identified and investigated two technologies that could make significant contributions to low carbon power supply in the UK; that of industrial combined heat and power, CHP, and tidal power. Life cycle case studies were completed on an existing UK CHP plant and the Severn Barrage scheme as it was proposed until 2010.

The Severn Barrage assessment has shown that the lifetime environmental impact is dominated by the operation stage. This is contrary to previously published studies, which have underestimated (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010)(Roberts 1982)(Spevack, Jones and Hammond 2011) or even ignored (Black & Veatch 2007)(Woollcombe-Adams, Watson and Shaw 2009)the contribution from this life stage. Furthermore, the results have demonstrated that the impact intensity of power from the Barrage is almost entirely reliant on that of the National Grid mix which provides the operational power required. It has been shown a large improvement to the impact of the operation stage can be made by removing the electricity demand for 'flood pumping'. However, even without 'flood pumping', the impact of the power demand for plant operation will dominate. Hence the greatest improvements to the schemes lifetime impact can be made via the National Grid mix itself.

The industrial CHP assessment has shown that there are large impact savings available from widespread implementation against the current and the baseline National Grid mixes. However, even if it is assumed that units are exclusively bio-gas fuelled, the carbon intensity of the power generated is very likely to exceed that of the low carbon Grid mix by 2050.

The discussion shows that the interactive roles that these two technologies could play, with each other and the evolving Grid mix, on the pathway to 2050 is, however, more complex than simply considering the isolated impact intensity. The commissioning of the Severn Barrage could mark the point at which the carbon intensity of the National Grid falls below that of CHP. However because the carbon intensity of the plant is reliant on the national power supply, it is argued that further CHP implementation should only be stopped if there is a suitable low carbon *and* low impact alternative that can fill the capacity gap. This thesis concludes that to fear that today's CHP schemes could represent a technology 'lock-in' in the long term future is to underestimate the role the technology has in the current and more short term future Grid mix.

The work presented demonstrates the importance of life cycle thinking in the development of a low impact energy strategy. The discussion has also shown the importance of scenarios in assessing the requirements for such an ambitious change. The pursuit of change implies that the future is necessarily dynamic. The work has illustrated that scenario thinking allows exploration of potential strategy decisions and hence, is essential to having confidence in the decisions made.

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Thanks for the companionship to everyone in the SERT team, particularly Glyn who, despite appearances, kept me sane – you may think I was helping you but you kept me on track more times than you know!

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But I dedicate this work to my unborn child, who has kicked and wriggled inside me for the last nine-ish months of the time I have spent writing. May this be one tiny pebble on the path to a better world for you.

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GLOSSARY

Carbon intensity	Carbon equivalent emissions per unit of power, inclusive of a 'basket' of greenhouse gases. In this research, carbon emissions will generally refer to life cycle rather than on site emissions.
Carbon negative	Exhibits a carbon (equivalent) reduction. Either actively removes greenhouse gases from the atmosphere or replaces a product or system with higher emissions in such a way that it is justifies a negative emission allocation
CCC	'*Climate Change Committee'*
CCS	Carbon Capture and Storage. The chemical process of removing the carbon from a fuel, either before or after combustion, and then storing it so that on site greenhouses gas emissions are minimized. In this work, the phrase 'CCS units' refers to fossil fuelled thermal power stations with a CCS facility
CHP	'*Combined Heat Power'* also known as Co-generation
DECC	*'Department of Energy and Climate Change'*
DUKES	'*Digest of UK Energy Statistics'*
EGR	'*Energy Gain Ratio'*
EIA	'*Environmental Impact Assessment'*
Energy intensity	Energy demand (or energy consumed) per unit of energy generated. In this research, energy demand will generally refer to life cycle rather than simple fuel demand.
EPSRC	'*Engineering and Physical Science Research Council'*
GWP	'*Global Warming Potential'*
LCA	*'Life Cycle Assessment'*
LCC	'*Life Cycle Costing'*
LCI	*'Life Cycle Inventory'*
LCSA	'*Life Cycle Sustainability Assessment'*
PFA	'*Pulverised Fly Ash'* or '*Fuel Ash'* is a by-product resulting from the burning of pulverised coal in coal fired power stations. It can substitute some proportion of the Portland cement required but it is never used in isolation (The Concrete Society 2002)
Ramsar Wetland Site	A wetland site recognised by the intergovernmental treaty '*The Convention on Wetlands* (Ramsar, Iran 1971) because of its ecological character (UN Treaty Series No. 14583 1971)
RDA	*'Regional Development Agency'*
SDC	'*Sustainable Development Commission'*

SEA	'*Strategic Environmental Assessment'*
SETAC	'*Society of Environmental Toxicology and Chemistry'*
SLCA	'*Social Life Cycle Assessment'*
Spark Spread	The difference in the retail price of electricity and the cost of the fuel to generate it. Specifically, if the former drops below the latter then electricity generation becomes financially unviable.
SSSI	*'Sites of Special Scientific Interest'*
STPG	'*Severn Tidal Power Group'*
UKERC	'*UK Energy Research Council*'

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CHAPTER 1. INTRODUCTION

The UK Government passed the Climate Change Act in 2008 and became the first nation to enforce carbon emission reduction targets up to 2050. It states that,

> "*It is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline*" (Her Majesty's Government 2008, Climate Change Act. Part 1.).

In order to meet this ambitious target it is widely thought that the UK energy future should be 'electrified' as a suite of low carbon generation technologies provide ever increasing proportions of electricity supply (Speirs, et al. 2010). The life cycle approach is slowly being realised as essential to estimating 'real' carbon intensity and, hence examining the relative roles that different technologies can, or can't, play in pursuit of a low carbon UK. Furthermore, the need to draw comparisons with an evolving grid in order to assess the contribution that any individual technology could make is becoming clear.

This research project carried out Environmental Life Cycle Assessment, LCA, case studies of two power generating technologies that have been identified as potential contributors to a pathway to a low carbon UK energy supply, that of industrial CHP and a tidal barrage: the former case study being on an existing CHP plant and the latter being the Severn Barrage scheme as it was proposed until 2010. The assessments use data from specific plants but the results can be considered generic examples of the technology type. This thesis will explain the two technology options selected for investigation and justify the choice via an exploration of each technology's history and potential in UK energy strategy. It will report on the comprehensive LCA case studies which have been carried out for each technology example, inclusive of a full inventory analysis and results interpretation. These case studies not only provide the data essential to the conclusions reached but will be of use to continue investigation into either one of the specific technologies.

The work presented in this thesis demonstrates the importance of life cycle thinking in the development of a low impact energy strategy. It showcases the importance of scenario based investigation in the pursuit of a truly sustainable energy future i.e. the implications of having to recognize and evaluate environmental gains in the immediate versus the long term within the context of an inherently dynamic system.

1.1 RESEARCH AIM AND OBJECTIVES

The aim of this research project was to determine the life cycle environmental impacts of proven power generating technologies that have the potential to contribute to a strategic pathway towards an ideal low carbon UK future. This overarching aim was achieved by completing the following four objectives:

a) ***To identify feasible but underexploited technology options for realising a low carbon UK energy mix***: The ideal UK low carbon power supply will consist of a number of generating technologies. It is typically thought that wind power, nuclear power and coal fired power with carbon capture and storage, CCS, will provide the majority of supply but that they will not bear the low carbon burden alone. Technology innovation is very important to developing diversity but there are existing solutions that have the potential for expansion. The case studied technologies were selected because they have been identified as having the potential to make a significant contribution to UK power supply but have thus far failed to do so.

b) ***To establish the life cycle environmental, energy and carbon impacts of these technologies and how they compare with the UK's energy past and potential future electricity supply mixes***: The life cycle or 'cradle to grave' approach is increasingly gaining recognition as the most appropriate way to account for the impact of any given product or system. The methodology was applied to the case study technologies in order to gain a 'true' picture of their impact. The research provides a wide picture of the environmental impacts of the case studied technologies and stresses that excellence in one impact area should not come at the cost of another. Comparisons were made with the specific life cycle impact results for power from the 1990 baseline, the current and three potential 2050 low carbon National Grid mixes (Hammond, Howard and Jones 2013), in order to provide context for the impacts of the identified, i.e. the magnitude of the impact benefits or costs they could offer.

c) ***To quantify whether these technologies could really help meet the UK carbon reduction targets:*** The focus of the UK reduction targets is carbon intensity, or global warming potential, GWP, so specific attention is given to the interpretation of the carbon result per unit of energy generated and the percentage savings available. However, assessing the roles that the case study technology could actually play in the ideal 2050 National Grid mix, is more complicated than calculating the specific savings against the 1990 baseline Grid. It is anticipated that the 2050 supply mix will actually have to have an emission intensity that betters the reduction target because it will also have to meet an increased demand. Therefore, a percentage analysis of the total power supply they could provide and the carbon emissions they would contribute relative to the current and ideal 2050 power supply was also completed.

d) ***To explore the roles that these technologies can play on the pathway to a sustainable energy future for the UK:*** The pathway to a sustainable energy future will be dynamic and complex, so analyses and decisions regarding specific technologies must be done relative to each other, to the current National Grid mix and to potential future Grid mixes. Life cycle thinking combined with a scenario approach is essential to making the comparisons required clear. Therefore the impact results generated combined with the pre-existing scenario narratives (Foxon, Hammond and Pearson 2010) were used as a basis to explore and discuss the interactive relationship that the two studied technologies could have with each other and with the National Grid mix on the pathway to 2050.

1.2 THESIS OUTLINE

This thesis consists of 11 chapters plus appendices. Figure 1 provides a visualisation of how the chapters are grouped in order to provide the thesis structure.

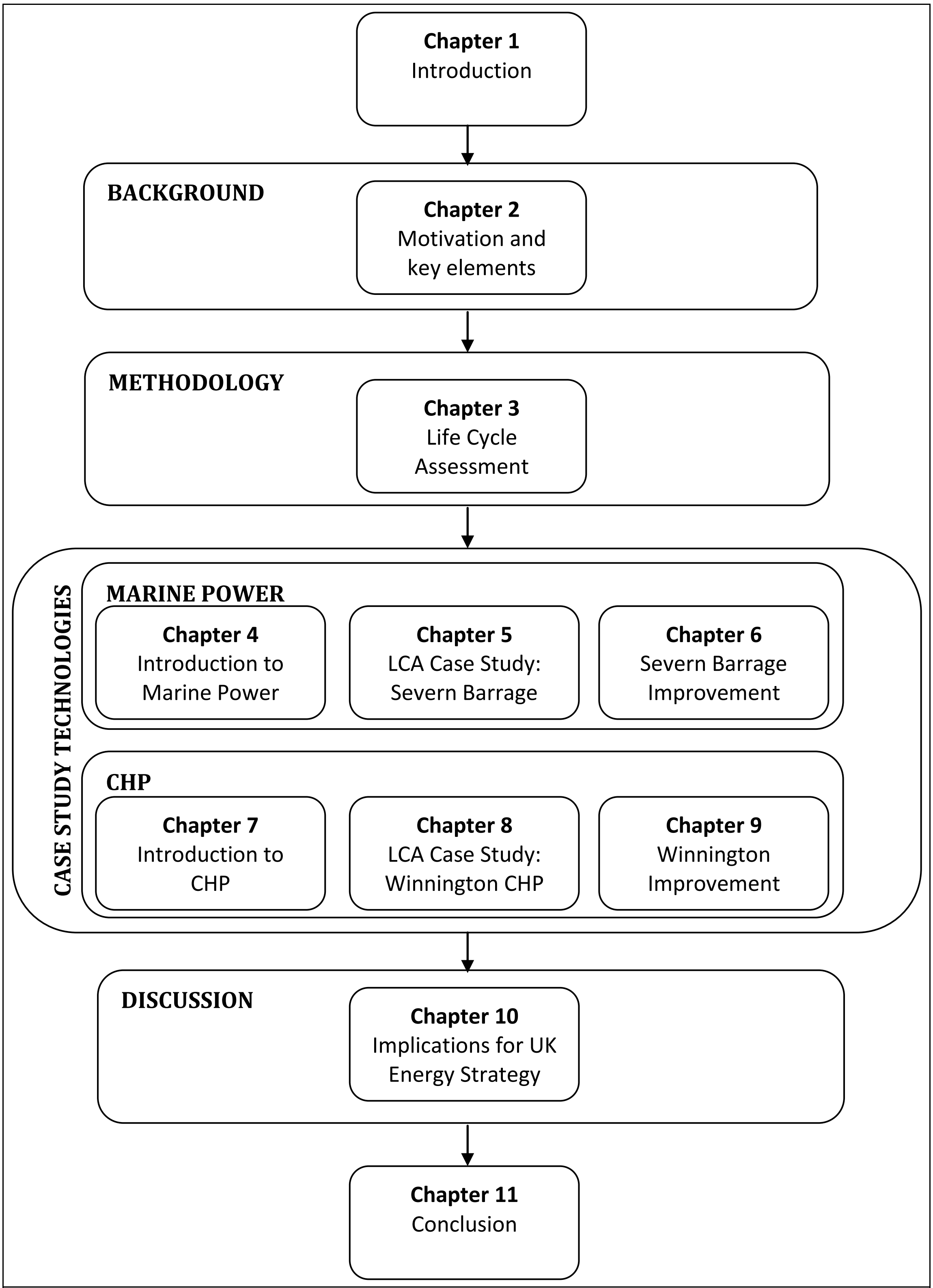


Figure 1 Schematic of thesis structure

This first chapter, entitled *Introduction*, presents the aim and objectives of the research project, describes the structure of the thesis and provides details of any incidences where the work has already begun to be disseminated. The remaining chapters present the following:

Chapter 2, *Background*, explains the motivation for the research. It details the need for sustainable energy solutions and the policy that is in place to drive the search for those solutions. Low carbon power generation technology options are discussed and the specific case study technologies are introduced. The life cycle approach is introduced and a summary of the development the Life Cycle Assessment methodology is provided. A brief summary of the scenario narratives generated by the Transition Pathways Research Consortium work and a justification for their use in preference to other scenario studies is given.

Chapter 3*, Methodology*, A detailed description of the stages of a Life Cycle Assessment makes up the majority of the chapter, inclusive of the specific Life Cycle Impact methodologies and Results Interpretation metrics used in this work. The limitations identified in the course of the research are also discussed. Specific data provided by the Transition Pathway's work is tabulated here and a description of its use in this research is provided.

Chapter 4, *Introduction to Marine Power*, provides a summary of the UK marine power potential, both in terms of the resource available and the technology development. It justifies the selection of the Severn Barrage tidal scheme for further assessment, as it is the largest single scheme proposed and uses the most established technology. A brief summary of the history of the scheme, the arguments against it and previously completed carbon and energy studies is also given. This work contributes to research objective (a).

Chapter 5, *LCA Case Study: Severn Barrage Tidal Power Scheme*, is a comprehensive report of the LCA carried out on the Severn Barrage tidal scheme. A thorough Inventory Analysis is presented which demonstrates the considerable improvements made in this assessment over those previously published. An extensive Results Interpretation is given, inclusive of the possible range of error generated by examining a variety of likely inventory choices identified. This work contributes to research objective (b) and (c).

Chapter 6, *Severn Barrage Improvement Analysis: Exclude 'flood pumping'*, explores the consequences of reducing the Barrage's life time power demand by operating the plant without 'flood pumping'; which is the act of reversing the turbines to pump water from the seaward side to the basin at each high tide in order to maximize the head deferential before generation begins. This work contributes to research objective (b) and (c).

Chapter 7, *Introduction to Combined Heat and Power*, gives a brief account of the history of CHP in the UK energy sector, inclusive of its current capacity. Descriptions of the technologies current and potential application in both the domestic and industrial sectors are given and the case against CHP as a low carbon energy generator is summarised. A review of assessments previously completed on various CHP types is carried out and the need for a further LCA of industrial CHP is justified. This work contributes to research objective (a).

Chapter 8, *LCA Case Study Winnington CHP Plant*, is a full report on the LCA carried out on the existing, E.On operated, natural gas fired, industrial CHP unit in Winnington, UK. The focus of the assessment is on the power generated by the plant. It is assumed that the power is generated as an additional benefit via harnessing the heat load that would have been produced anyway. Appropriate allocation methods are explained for investigating the impact of the power within and without the context of this premise. Detailed Inventory Analyses are given of both the plant itself and of those needed to assess the hypothetical separate systems required to appropriately apply the allocation methods. A Results Interpretation that is in line with that carried out for the Severn Barrage study is presented. This work contributes to research objective (b) and (c).

Chapter 9, *Winnington Improvement Analysis: Alternative Fuel*, re-assesses the Winnington plant but under the assumption that purified bio-gas, derived from waste streams, is used to fuel the plant and presents the impact improvements that are identified. This work contributes to research objective (b) and (c).

Chapter 10*, Implications for UK Energy Strategy*, discusses the roles that the technologies could have in and on the pathway to the 'more electric' energy future as far as 2050. The contribution to carbon and, separately, impact reduction are explained in light of the findings of the LCA case studies. The supply capacities suggested by the Transition Pathway's scenarios are used to explore and better demonstrate the complex and interactive factors that would affect the suitability of these technologies in a necessarily dynamic and uncertain future. This work contributes to research objective (c) and (d).

Chapter 11, *Conclusion*, gives an overarching summary of the research completed, proposes required further work, summaries the original knowledge contribution and, finally, provides a list of concluding recommendations.

1.3 DISSEMINATING THE RESEARCH

The initial results of the Severn Barrage case study were published in the international journal *Energy* in 2012 (Kelly, McManus and Hammond 2012), see Appendix C and further work was also published by the UK Commons Select Committee as part of their inquiry (K. A. Kelly 2012), see Appendix D.

The initial results of the CHP LCA case study were presented at the Transition Pathways Dissemination Conference in 2012 and at the 7th Conference on Sustainable Development of Energy, Water and Environmental Systems, SEDEWES, as a keynote presentation to the Energy Systems session, later in the same year. The SDEWES conference paper is included as Appendix E to this thesis.

The overall work, was presented at the SETAC 18th LCA Case Studies Symposium under the title, 'Jam today verses jam tomorrow: The role of life cycle thinking in strategizing for a low carbon energy mix in the immediate and long term'.

CHAPTER 2. BACKGROUND

2.1 IN THIS CHAPTER

This chapter sets the scene and explains the motivation for this research work by introducing all the major elements of the project. It details the need for sustainable energy solutions and the policy that is in place to drive the search for those solutions. Low carbon power generation technology options are discussed and the specific case study technologies are introduced. The life cycle approach is introduced and a summary of the development the Life Cycle Assessment methodology is provided. A brief summary of the scenario narratives provided by the Transition Pathways Research Consortium work and a justification for their use in preference to other scenario studies is given.

2.2 SUSTAINABLE ENERGY

A fundamental definition of 'sustainability' is simply the capacity of a thing to continue, whether that is a living creature, a lifestyle or a system. Conversely, when a creature, lifestyle or system exhibits or promotes behaviour that compromises its ability to continue, it becomes unsustainable. It is generally agreed that we, the human race intend to continue and as such we should ensure that our behaviour is consistent with obtaining and maintaining our sustainability.

The enduring definition of sustainability is presented in the, so-called, Brundtland Report as,

> "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development 1987).

In order simplify this ideal and to encourage stakeholder engagement, i.e. industry and governments, John Elkington coined the phrase the '*Triple Bottom Line*' and set down the three pillars of sustainability of 'social, environmental and economic' (Elkington 1997). It may often seem that the interests of one are in conflict with the interests of at least one of the others but true sustainability cannot be achieved until all three are satisfied.

One of the trade mark behaviours of the human race is the manipulation of energy to meet our needs, starting from the first human who made fire or, in engineering terms, converted a potential energy source into heat and light. So in order for the human race to continue as we know it, to be sustainable, we must secure sustainable sources of energy.

Since their discovery, human energy generation has been increasingly reliant on fossil fuels. Fossil fuels can be considered a finite reserve (within the boundaries of human history) so a continued reliance on them is impossible. The burning of fossil fuels releases certain gases into the atmosphere which intensify the so-called 'greenhouse effect' and bring about global warming. Continued global warming will bring about irreparable global climate change. Adopting energy generation techniques that use fossil fuels more efficiently or, ideally, use renewable and/or low carbon fuels, is essential to achieving sustainability.

Over the last 3 decades or so considerable discussion has gone on between and within the world's governments about the problems of current energy practices. Discussions focus on what extend we should change these practices, how we can ensure the changes happen and how can we enact these changes without jeopardising the development of those countries yet to fully undergo an industrial revolution. The Kyoto Protocol was the first Global Agreement to act to reduce global greenhouse gas emissions. It established 1990 emission levels as the base case and binds willing nations to reduction targets.

2.3 THE UK LOW CARBON CHALLENGE

In 2008 the UK Government Passed the Climate Change Act and became the first nation to enforce 'greenhouse' gas, GHG, reduction targets up to 2050. It states that,

> *"It is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline."*(Her Majesty's Government 2008, Climate Change Act. Part 1)

It splits the years leading up to 2050 into 'carbon budgetary periods' of 5 years with ever increasing reduction targets. The system allows the 'banking' and 'borrowing' of carbon budgets between periods. *'The Carbon Plan*' was published by the UK Government in December of 2011. It set out carbon reduction targets for the four budgetary periods of 2008-2012, 2013-2017 2018-2022 and 2023-2027 at 23%, 29%, 35% and 50% below the 1990 baseline, respectively (Her Majesty's Government 2011, The Carbon Plan. Table B1).

2.3.1 THE ALL ELECTRIC CONSENSUS

The energy sector is commonly split into the three main groups of power, or electricity generation, heat and transportation. It is generally thought that there are more opportunities for low carbon and/or fossil free power generation than there are for either heat generation or transportation. The '*Carbon Plan*' states that,

> "*The oil and gas used to drive cars, heat buildings and power industry will, in large part, need to be replaced by electricity, sustainable bioenergy, or hydrogen*." (Her Majesty's Government 2011, 4).

Numerous studies have suggested that the shortest route to low carbon heat and transport is via electricity. This is emphasis on power generation that is found in so many strategic studies is sometimes referred to as the 'all electric consensus' (Speirs, et al. 2010) and this paints the picture of a 'low carbon, more electric future'(Hammond, Howard and Jones 2013) for the UK. Hence this research focuses on the decarbonisation of the UK electricity sector. Figure 2 shows the reported emissions for the UK power sector between the base year 1990 and 2010 and the maximum allowable emissions to 2050 as defined by the UK reduction targets stated in '*The Carbon Plan*'. These emissions levels are considered a maximum as it is thought that power sector will have to decarbonise at a greater rate in order to compensate for the heat and transport sectors where reductions may well be harder to achieve.

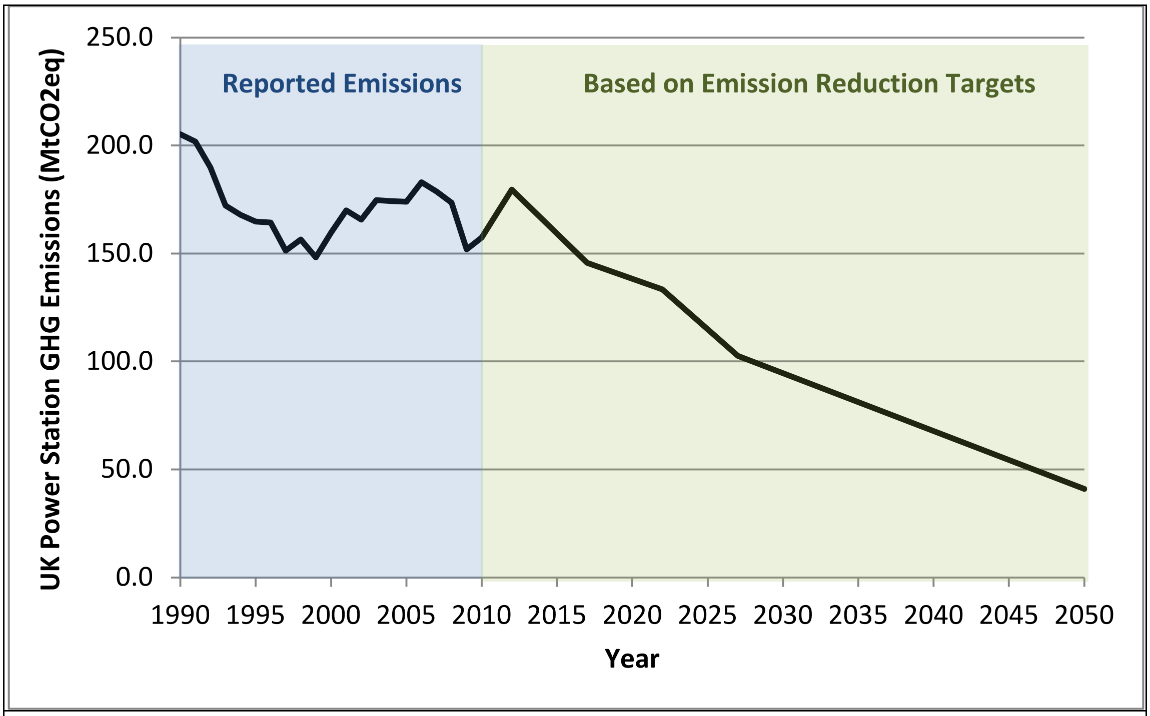
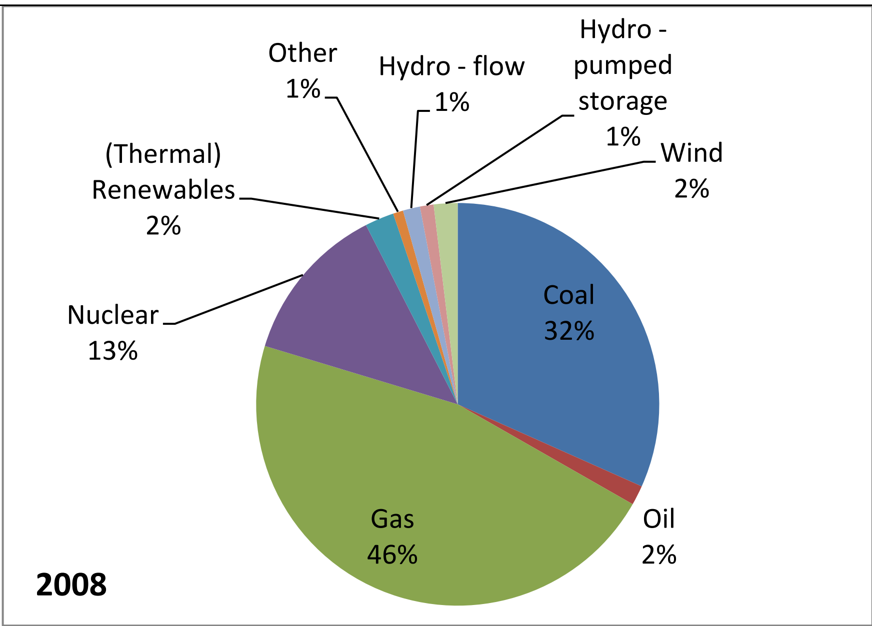


Figure 2 Graph of historic (Office for National Statistics 2013, UK Emission Statistics. Table 3)and target(Her Majesty's Government 2011, The Carbon Plan. Table B1) GHG emissions for UK Power Stations

Figure 3 shows the technology spread for UK electricity supply in 2008, which is taken to represent the 'current' year for the majority of the analysis presented in this thesis[1], and in 2011, which was the most up to date data available at the time of writing. It can be seen that there was some shift from fossil fuel dependence to nuclear and renewable energy sources between 2008 and 2011. In fact the overall power supply fell from 373 TWh to 351 TWh between 2008 to 2011, so the actual reduction in fossil fuels consumed could be greater than implied by these graphs. The energy reduction by 2011 can be largely attributed to a reduction in UK home industry due the economic recession and to the outsourcing of manufacturing to foreign factories. The latter case does not really result in an avoided fossil fuel demand but this cannot be represented when considering domestic supply only. The most important point that Figure 3 demonstrates is that even in 2011, 21 years after the baseline year of 1990, the UK power supply mix is over 70% dependant on the burning of fossil fuels. There is still an enormous amount of technology change required if the carbon reduction targets are to be met.

[1] 2008 is used to represent the 'current' year in line with the LCA work completed by the Transition Pathways research work (Hammond, Howard and Jones 2013).



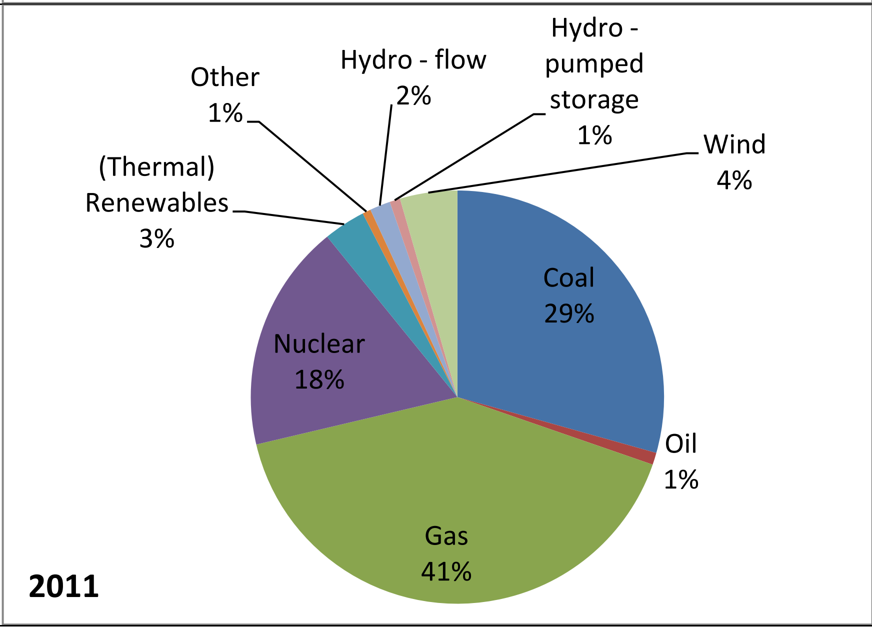


Figure 3 'Current' electricity supply (gross) by technology type (Her Majesty's Government 2012, DUKES. Table 5.6)

2.3.2 LOW CARBON POWER GENERATION OPTIONS

The '*Low Carbon Plan*' states that,

> *"Electricity will need to be decarbonised through renewable and nuclear power, and the use of carbon capture and storage (CCS)."* (Her Majesty's Government 2011, p. 4).

On and off shore wind power is typically considered to be the largest opportunity for renewable power generation in the UK. Gross power supply from wind energy rose from 7 TWh to 16 TWh between 2008 and 2011 (Office for National Statistics 2013, UK Emission Statistics. Table 3). It has been estimated that the UK is the windiest country in Europe and that the resource could, theoretically, provide over 1000 TWh(e) per year (Department of Trade and Industry 2001, UK wind resource). However, this is clearly a huge increase on the 2011 capacity and it would be unrealistic to suppose that even a majoritive share of this could be realised by 2050. Some proportion of the resource simply could not be converted into useful power as it would be at wind speeds unsafe for current turbines. Also, the wind does not necessarily blow at the time that power is required, so considerable storage facilities will have to be brought on line for effective supply side management. There is also still substantial objection to the installation of wind farms on aesthetic grounds.

Nuclear power has the potential to satisfy a large proportion of the UK energy demand whilst producing very little waste and emitting negligible CO_2 when compared to conventional fossil fuel based generation. Gross power supply from nuclear energy rose from 48 TWh to 63 TWh between 2008 and 2011 (Office for National Statistics 2013, UK Emission Statistics. Table 3). Strong opposition to nuclear remains and mainly focuses on the safety issues surrounding the disposal of dangerous waste and the potential of core melt down. Disasters, such as Chernobyl and Fukushima, are often used as examples of how vulnerable an area can become once a nuclear plant is installed. Less emotive opposition is also raised with regard to the energy and emissions associated with fuel extraction and preparation, waste disposal and plant construction and decommission. Also with regard the lead time to construct plants, specifically how much CO_2 will be emitted by conventional generation plants i.e. coal and gas, while the construction is undertaken to meet required nuclear capacity.

Carbon capture and storage, CCS, technologies involve the removal of carbon from fossil fuels (typically coal), before or after combustion, then storing it in a way that prevents it entering the atmosphere. This technology is yet to be proven on a large scale. Even if the technology is shown to be effective, the problems associated with security of supply of fossil fuels remain and, in fact, would be exacerbated as the addition of a CCS facility would reduce the fuel efficiency of the generating plant.

Even if the specific limitations of the three main low carbon technologies were instantly overcome, the scale of investment, construction and material consumption that would be required in order to replace the necessary reduction in fossil fuelled generation would be unprecedented. A considerably more diverse technology mix is necessary.

2.4 INTRODUCTION OF CASE STUDY TECHNOLOGIES

This research has focused on establishing and assessing technology options that are distinct from the three technology options, described above, that typically form the majoritive share of any hypothetical low carbon Grid mix; specifically the Severn Barrage and industrial combined heat and power, CHP.

Both tidal barrages and CHP represent examples of proven low carbon electricity generating technologies that have significant untapped potential in the UK. The Severn estuary boasts the second largest tidal range on Earth (The Environment Agency 2013). It provides the opportunity for one of the largest renewable power installations in the world. Harnessing the established heat load within UK industry to generate electricity via CHP would provide a significant opportunity for both low carbon power and national fuel efficiency. Despite this, both technologies also have a long and disappointingly sluggish history in the UK. The idea of installing a tidal barrage in the Severn estuary has been around in UK energy discussions for nearly 100 years but a final design, let alone a date to begin construction, still seems remote. Despite the technology having been established in the UK since the late 1800s, CHP has failed to reach the sort of widespread implementation that it has in other Northern European countries. Arguably, the slow up take of both can put down to resistance from successive governments to invest or incentivize either one.

In terms of the potential contribution to the UK's energy future, however, they represent polarized approaches. CHP implementation, particularly on industrial sites, has a short lead time (relative to other low carbon options) and can provide carbon reductions compared to the current supply, helping slow climate change today, but it is feared that primary fuelled CHP could become an anachronism in the 'all electric' future. In contrast, installation of the Severn Barrage would take at least 8 years plus the time required to re-review the proposal before construction can even begin. If the Barrage were commissioned, however, it would generate predictable, renewable energy for at least its design lifespan of 120 years, stretching far beyond 2050.

2.5 ENVIRONMENTAL LIFE CYCLE ASSESSMENT

Life Cycle Assessment, LCA, aims to account for the environmental burden of a given product or service across its whole lifetime, from material extraction to manufacture to use to disposal or from 'Cradle to Grave'. In this way, the LCA approach introduces two main conceptual steps forward for energy and environmental analysis:

- The consideration of the whole life time. Other, simpler, assessment methods will tend to focus on which ever stage of life is most familiar to the assessor or perceived to be the most impactful. This can lead to the exclusion of significant factors due to, fairly arbitrary, geographical or temporal boundaries. For instance, the impacts of material extraction and disposal are often completely excluded; construction methods can be demonized despite product longevity or, conversely, ignored in favour of a use only assessment.
- The consideration of a suite of impacts. Using the LCA approach means that an inventory model is developed which can be used to assess a number of potentially impactful resource demands or emissions simultaneously. Most other assessments will focus on only one environmental impact, typically resource or energy consumption, or carbon emissions. This can potentially lead to decisions that minimize one environmental impact whilst exacerbating another.

The life cycle approach was considered essential to the completion of this research because of these aspects of the methodology.

2.5.1 HISTORY AND CONTEXT

The first recognizable LCAs were carried out in the late 60s. During the 60s, the idea that the earth was not the limitless resource provider and waste disposal system it was previously assumed to be began to creep into mainstream thinking. The publication of Carson's '*Silent Spring'* (Carson 1962) in 1962 and Meadows', '*The Limits to Growth'* (Meadows, et al. 1972)10 years later provide literary evidence of the shifting attitudes of the time, as well as providing the manuals for the sustainability movement up to the present day. The debate over appropriate material use and waste reduction came to focus on product packaging and the LCA approach largely grew out of the desire to add science and numbers to the debate. Between 1969 – 1972 early 'LCAs' focused on almost exclusively on packaging and were typically commissioned by commercial production companies (Baumann and Tillman 2004). Coca Cola is often cited as having commissioned the very first LCA study in 1969(Baumann and Tillman 2004). The company was looking for an environmentally friendly alternative to metal drinks cans and wanted to quantify the environmental consequences as well as energy demand and material requirements of the options, from material extraction to disposal. It is reported that energy and material use were included in the study because Coca Cola felt that these factors were inherently linked to environmental impact. A hypothesis that environmentalists and LCA practitioners now know to be true, but it is also likely that energy and material use was of interest to Coca Cola as these factors are directly linked to cost.

The capacity for the LCA approach to enable resource and hence financial efficiency meant it became hugely prevalent during the early 1970s as the oil crisis took hold. However the focus on energy over any other impact meant that the energy specific methodology of 'energy analysis' is more commonly associated with this era. Energy analysis applies LCA methodology to account for energy flows only; other materials used and/or waste produced is excluded. The methodology for this specific application was 'codified' at an International Federation of Institutes for Advanced Studies, IFIAS, workshop in 1974; this predates any major efforts to formalize LCA methodology in its wider sense but the principles can be instructive to the LCA practitioner today. The energy analysis approach was defined as,

> " …*the determination of the energy sequestered in the process of making a good or a service*…." (IFIAS 1974).

This definition can be extended to include all energy and/or materials sequestered and/or pollutants emitted in the process of making, using and disposing of a good or service.

Following recovery from the oil crisis in the latter half of the 1970s, interest in energy analysis, or in any LCA application, lapsed. Until, that is, environmental concerns were raised again, triggered by a series of high profile environmental disasters and campaigns throughout the 1980s, e.g. the Union Carbide chemical catastrophe in India in 1984, the Chernobyl disaster in 1986, a sequence of off shore oil spills and the campaign against CFCs for protection of the ozone layer. LCA studies became increasingly widespread as companies strived to improve their environmental credentials. However there was also an increasing feeling that, like so many modelling methodologies before it, there was scope to manipulate the results of an LCA. Any studies that favoured the product of the company that commissioned the study, particularly, lacked credibility. By the 1990s, LCA was recognized as an important tool but the need for regulation was clear. In 1990, the International Professional Association for Environmental Affairs predicted that Life Cycle Assessment would be, "… *one of the most important tools for decision making* […] *of the 1990s*…" but went on to state that LCA techniques were fraught with methodological problems and that it was, "… *commonly felt* …" that the scientific basis for assessing the environmental impact of products was inadequate (Baumann and Tillman 2004). In response to this, the Society of Environmental Toxicology and Chemistry, SETAC, ran the first international academic conferences and workshops in LCAs in the 1990s and published the first set of method guidelines in their '*Code of Practice*' in 1993. Following this, the International Organisation for Standardization began formalizing a methodology framework and a series of ISO standards have since been published which, among other things, set the minimum required format of an LCA study as set out in Chapter 3 of this thesis.

2.5.2 THE FUTURE OF LIFE CYCLE THINKING: LIFE CYCLE SUSTAINABILITY ASSESSMENT

Most recently, developments have focused on the application of life cycle thinking to assess environmental, economic and even social impacts simultaneously and hence develop a full Life Cycle Sustainability Assessment. 2010-2020 has already been described as the, "*Decade of Life Cycle Sustainability Analysis*" (Guinée, Heijungs, et al. 2011) and an analysis framework is emerging. In its simplest form, a Life Cycle Sustainability Assessment, or LCSA, can be seen as the sum of a representative life cycle based assessment for each of the three pillars of sustainability i.e. an environmental LCA, a Life Cycle Cost assessment, LCC, and a Social LCA, SLCA, as shown in the following equation:

LCSA = LCA + LCC + SLCA (Klöpffer and Renner 2008)

Environmental LCC is an economic assessment but with the inclusion of the monetary costs of the life cycle environmental flows, i.e. a 'real' rather than a face value cost inclusive of resource depletion, toxic emissions etc. LCC is general considered the oldest of the three separate disciplines and has its origins have been credited to systems engineers in 1978 (Swarr, et al. 2011) and United States of America General Accounting Office in 1933 (Ciroth, et al. 2011). A formal code of practice for the use of LCC in a LCSA was published by SETAC in 2011. Social LCA, is probably the most immature of the disciplines. The consideration of societal effects has a long history in sociology, politics and so on but the cultural differences between the qualitative approach of social science and the quantitative approach of engineering and economics has long proved a barrier to developing a truly joint methodology rather than parallel but separate ones. The joint UNEP and SETAC 'Life Cycle Initiative' published a set of SLCA guidelines in 2009 (Andres, et al. 2009). The focus of the development of the LSCA has been, and will surely continue to be, on an appropriate convention for combining the three separate assessments into one i.e. on the setting of appropriate and consistent system boundaries and on the characterization, normalization and potential weighting of a full suite of LSCA impact categories. There are many issues remaining within each separate discipline, with regards to reliably and repeatably valuing impact let alone using that impact value in a further discussion of what is sustainable. Hence being able to successfully combine the disciplines to make a coherent assessment seems unwieldy at best. However, as is often the case with assessments, if nothing more than a list of further questions and considerations is generated that, in itself, is infinitely greater than nothing.

It has been stated that,

> *"Life cycle thinking is the prerequisite for any sound sustainability assessment. It does not make any sense at all to improve (environmentally, economically, socially) in part of the system in one country, in one step of the life-cycle or in one environmental compartment if this improvement has negative consequences for other parts of the system which may outweigh the advantages. Furthermore, the problems shall not be shifted into the future".* (Klöpffer and Renner 2008)

The last point seems to be the most crucial to truly assessing sustainability within the conventional understanding of it, which for the current generation of analysts (of all disciplines) is the Brundtland definition (World Commission on Environment and Development 1987), which, clearly instructs them that future and immediate gains or losses should be treated with equivalent value in order to be sustainable. However in the most prevalent and well established discipline of economic analysis, the remoteness of future events has typically been treated to be inversely proportional to their certainty and, hence is usually treated as an indicator of their significance. So in economics and, subsequently, any analyses that use econometrics as a template, discount factors are typically applied. 'Future utility discounting', as it is sometimes called, leads to results that favour more immediate benefits and hence, arguably, unsustainable actions. Early advocates of sustainability have already described the use of future discounting as unethical (Meadows, et al. 1972). It remains to be seen how LCSA will develop to deal with the problem of future uncertainty whilst maintaining the pursuit of inter-generational fairness. This may have wide reaching consideration throughout the methodology. The IPCC methodology for characterising climate change already includes a range of factors for different timeframes, see further explanation in section 3.5.2; should a range of time frames be offered for each impact category? Should a range of potential future reference systems be developed for future-proof normalisation? See section 3.5 for a full explanation of characterisation and normalization. It has been proposed that to truly safeguard the 'needs' of future generations, as Brundtland would wish, in an LCSA, at least two assessments should be carried out; one for 'now' and one for 'then' (Mattila, Seppälä and J 2012) but then the problem of how to combine multiple assessments back into one resurfaces.

2.6 SCENARIO THEORY AND USE

The assessment case studies completed reveal a lot about each technology in isolation. However, one of the reasons for selecting these two particular technologies was because of the different approaches they represent in pursuing a more sustainable energy future. In order to investigate the roles that these technologies could play in that pursuit more thoroughly, existing scenario narratives were used.

Scenarios are hypothetical snapshots of the future and outline the significant events that need to occur for that future to be realised. Broadly speaking these two components are differentiated by designating the 'scenario' as the endpoint and the events as the 'pathway'. Scenarios can provide invaluable assistance when developing or assessing a strategic plan for an uncertain future.

Numerous scenario studies have been carried out. The Climate Change Committee, CCC, the UK Energy Research Centre, UKERC, and the Department of Energy and Climate Change, DECC, have all completed scenario work (Speirs, et al. 2010) that have contributed to the development of Government policy and the '*Low Carbon Plan*'. However, these studies have typically only considered basic on site emissions. This research project has only used the work completed by the Transition Pathways Research Consortium (Transition Pathways Consortium Team n.d.).

2.6.1 TRANSITION PATHWAYS TO A LOW CARBON ECONOMY

The Transition Pathways Research Consortium, consisting of representatives from 9 UK Universities in collaboration with E.ON and the EPSRC, have proposed three different scenarios for how the UK energy landscape could develop up to 2050 and the resultant technology mix for the UK National Grid (Foxon, Hammond and Pearson 2010). The three scenarios can be summarised thus:

- Central Control: The government is the main actor. The electricity supply mix is characterized by large, centralized schemes, predominately nuclear but also including CCS, wind farms and a tidal barrage.
- Market Rules: Industry is the main actor. The electricity supply mix is characterized by large, centralized schemes predominately CCS but also including nuclear, wind farms and a tidal barrage.
- Thousand Flowers: Consumers/citizens are the main actors. The electricity supply mix is characterized by smaller, decentralized schemes, including gas and biomass

district heating and solar. Energy efficiency and demand reduction has greatest significance in this scenario.

Uniquely, however, the consortium has completed carbon focused Life Cycle Assessments, inclusive of upstream emissions. The project consortium has generated life cycle inventories for all three the Grid mixes at intervals up to 2050. Hence the specific life cycle impact, carbon or energy intensity for each hypothetical Grid mix can be obtained for comparison. This data is provided along with a discussion of how it was used in this research work in section 3.6.3.2. This provision of life cycle data alone makes the Transition Pathways scenario work the most appropriate reference for this research but the overall approach to technical feasibility in the development of the narratives was considered more realistic than other scenario studies. Also, a perhaps incidental but non-the-less important factor in selecting the Transition Pathways work, was that the author of this thesis was able to be actively involved with the consortium which has provided considerably more context, guidance as well as raw data than could have been obtained otherwise.

Further detail of the Transition Pathway Research project approach along is provided in Appendix A.

2.7 SUMMARY

It is increasingly accepted that a large shift in behaviour is required by all of human kind in order to maintain our existence as we know it. This is the pursuit of sustainability. Securing sustainable energy is now a priority worldwide. Since their discovery, human energy generation has been increasingly reliant on fossil fuels. The continued use of fossil fuels in the conventional way is contrary to the pursuit of sustainability because it they are a finite fuel source and because of the resultant carbon emissions that lead to climate change.

The Kyoto Protocol was the first Global Agreement to act to reduce global greenhouse gas emissions. It established 1990 emission levels as the base case and binds willing nations to reduction targets. In 2008 the UK Government passed the Climate Change Act and became the first nation to enforce 'greenhouse' gas, GHG, reduction targets up to 2050. In order to meet these targets it is widely thought that the UK energy future should be 'electrified' as a suite of low carbon generation technologies provide ever increasing proportions of electricity supply. In 2011, over 70% of the UK electricity supply was provided by fossil fuels. Considerable technology change is required. The three main technologies that typically form the majoritive share of any hypothetical low carbon Grid mix are: wind power, nuclear power and fossil fuelled generation with carbon capture and storage, CCS. Each of these technologies have some specific limitations but even if these were instantly overcome, the scale of investment, construction and material consumption that would be required in order to replace the necessary reduction in fossil fuelled generation would be unprecedented. This research has focused on establishing and assessing technology options that could help form a more diverse mix, specifically the Severn Barrage and industrial combined heat and power, CHP. Both tidal barrages and CHP represent examples of proven low carbon electricity generating technologies that have significant untapped potential in the UK.

The life cycle approach is essential to estimating 'real' carbon intensity and, thus, examining the relative roles that different technologies can (or can't) play in pursuit of a low carbon

UK. Hence, this is the methodological approach adopted for assessment of the technology examples chosen. Life Cycle Assessment studies, LCAs, have been carried out since the '60s, but the methodology was standardised in the '90s (Baumann and Tillman 2004). The future of LCA, and perhaps of any system analysis, lies in developing a multidiscipline approach which will enable truly sustainable decision making. However there are many hurdles remaining with respect to satisfactory interlacing of, thus far, separate assessment types and to developing a formal approach for achieving intergenerational fairness, which, according to Brundtland (World Commission on Environment and Development 1987), should be at the heart of the pursuit of sustainability.

Existing scenario narratives were used in this research work in order to investigate the roles of the individual case study technologies in pursuit of a more sustainable energy system. Scenarios are hypothetical snapshots of the future and outline the significant events that need to occur for that future to be realised. This research project has only used the work completed by the Transition Pathways Research Consortium (Transition Pathways Consortium Team n.d.). The consortium has published three distinct scenarios entitled, Central Control, Market Rules and Thousand Flowers. The consortium work was used in preference to other scenario studies because it has generated life cycle inventories for all three Grid mixes at intervals up to 2050. This has provided appropriate data to contextualise and assess the results generated by this research work.

CHAPTER 3. METHODOLOGY: LIFE CYCLE ASSESSMENT

"Lo que se mide se mejora"

- Spanish saying

3.1 IN THIS CHAPTER

This chapter explains the principles and methodology of Environmental Life Cycle Assessment, why it has been adopted for the technology case studies carried out and the specific ways in which the methodology has been applied in this work.

3.2 INTRODUCTION

The life cycle approach is slowly being realised as essential to estimating 'real' carbon intensity and, hence, to examining the relative roles that different technologies can, or can't, play in the pursuit of a more sustainable energy future for the UK. A Life Cycle Assessment, LCA, represents a more thorough representation of the impact of a product or service because it can:

- provide a fuller account of the total relevant impact flows across the study subjects whole life time, regardless of temporal or geographical constraints
- generate an inventory model which can be used to assess a suite of environmental impacts, rather than focusing on just one

The International Standard Organisation, via the British Standards Institute, provides the, '*Principles and framework'* for a standardised LCA within ISO 14040:2006(Standards Policy and Strategy Committee 2006) and the, '*Requirements and guidelines*' within ISO 14044:2006(Standards Policy and Strategy Committee 2006).

The ISO standards state that an LCA must include the following four phases:

- The *goal and scope* definition phase, which should include the system boundary and level of detail. Like most assessments, the scope of an LCA depends on the subject and the intended use of the study so the depth and the breadth of LCA can differ considerably.
- The *inventory analysis* phase involves collection of the data necessary to meet the goals of the defined study. The outcome is a life cycle inventory, or LCI, of materials and processes, and their associated resource and waste flows with regard to the system being studied.
- The *impact assessment* phase which provides additional information to help assess a product system's LCI results so as to better understand their significance in terms of environmental impact.
- The *results interpretation* phase summarizes and discusses the results of an LCI or an impact assessment, or both, as a basis for conclusions, recommendations and decision-making in accordance with the *goal and scope* definition.

The structure of an LCA can be explained using the visualisation shown in Figure 4 below.

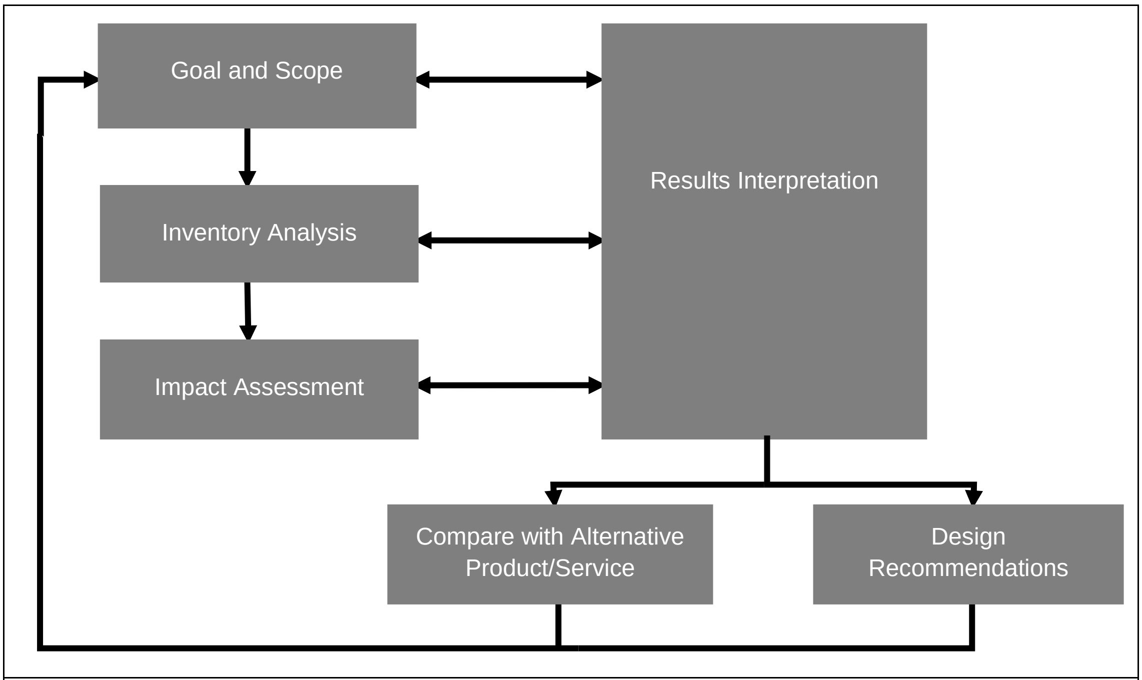


Figure 4 Visualisation of the structure of a Life Cycle Assessment

3.3 GOAL AND SCOPE

Defining the *goal and scope* is arguably the most important stage of an LCA, as it requires identification of the assessment purpose and sets the assessment boundaries. The 'functional unit' should be explained, also any need for allocation should be identified, and methods used justified, in the *goal and scope*.

3.3.1 STUDY BOUNDARIES

The LCA approach does allow the practitioner to surpass geographical and temporal boundaries, however for the sake of project management and reasonable results' comprehension, it is essential to set study boundaries of some kind on the *inventory analysis*. An appropriate boundary will often become clear once the purpose of the study has been defined. In practice, and largely for the case studies presented in this thesis, the inventory boundary is set by what data is available and the boundary of any study which will be used for comparison in the results interpretation.

3.3.2 FUNCTIONAL UNIT

LCAs are often used in the context of a comparison, and this was frequently done in the work present in this thesis, hence it is important to express the results in an easily comparable form. This is the functional unit. Taking the Coca Cola example(Baumann and Tillman 2004), the goal of the study was investigate the least environmentally impactful way of packaging the drink. It may seem appropriate to calculate the impact of one glass bottle but this won't necessarily help make the decision between glass bottles and aluminium cans, particularly if the options are of different volumes or if the glass bottles are typically reused. Hence it might be better find the impact of each packaging option *per litre of drink dispatched.* The case studies in this work focus on electricity generation, so the functional units will usually either be impact per whole lifetime or impact per unit generated, sometimes called 'specific impact'.

3.3.3 ALLOCATION

If the product or process being assessed has one or more co-products, or by-products or is, itself, a by-product, the goal and scope should state the way, or ways, that the total impact is allocated. The most appropriate method might be by mass or financial value, or by desired outcome which would, by definition, totally discount any truly qualifying 'by-products'. In practice, anywhere allocation may be controversial it is better to apply a few viable allocation methods and provide an impact range in the results. This approach was adopted in the CHP case study reported in Chapter 8, allocation between the heat and power generated is crucial to the case study results so allocation methodologies are explored.

3.3.4 USE OF LCA SOFTWARE

Managing the data streams required and created by an LCA project can be extremely complex. Commercially available software is often used to simplify the task. The software package SimaPro v7.3.3 (PRé Consultants 2011) was used throughout this research project.

3.4 LIFE CYCLE INVENTORY ANALYSIS

Once these aspects have been established, data is collected and organised into a life cycle inventory, or LCI. The *inventory analysis* stage is, almost always, the most time consuming part of the LCA process. The LCI should consist of all the environmentally relevant inflows and outflows of the assessment subject, within the system boundaries defined by the *goal and scope*. Establishing an appropriate LCI to meet the requirements set out in the *goal and scope* should be seen as a modelling process and much more than a list-making activity. It is necessary to iteratively improve the *inventory analysis* following the results of the remaining stages of the LCA process.

3.4.1 INVENTORY DATA RESOURCES

In order to create an appropriate inventory, a large amount of data is required. The three main sources of data used for the work presented, and most LCA studies, are:

- Commercially available inventory databases: e.g. EcoInvent (EMPA 2007)
- Publically available data: e.g. published academic studies, government reports
- Privately available data: from the company or organization that own/operate the product

3.4.2 LIMITATION AND UNCERTAINTY

The main areas of modelling uncertainties and, hence, LCA limitations identified in the course of this research are mainly with respect to the LCI compilation:

- Data cut off: to include every resource flow in the LCI, a huge volume of data would have to be collected and is practically impossible. The point at which further data collection would cease to improve the model must be decided by the LCA practitioner and this is usually more than a little influenced by time restrictions.
- Limited subject knowledge of the LCA practitioner: the LCA practitioner cannot always be an expert on the study subject so will have to interact closely with people who are and take their advice on what should be included in the LCI. These experts may know very little about the LCA approach so building this relationship can be time consuming and challenging in itself. It may also mean that the LCI will need constant revision as the study progresses as more experts and/or more data becomes available.

- Simplification of products or processes for the LCI: related to the above, even if the practitioner has a satisfactory list of entries for a robust LCI, as with all modelling, a degree of simplification is necessary and, as with all modelling, it is the decision of the modeller as to the extent of the simplification.
- Limitations of LCI databases: the modeller is also likely to use a good deal of information from an existing database to fill in data gaps or as guidance on acceptable simplification. The databases will also have been developed subject to necessary simplification and data limitations.
- LCI database choice: databases are likely to include a number of potentially applicable options for identified data gaps, for instance which entry for 'steel' is the best representation for the 'steel' in the study subject? So it then becomes the practitioner's responsibility to choose the most appropriate entry

These limitations and uncertainties of the LCI can be addressed via robustness assessment and sensitivity tests which can justify and contextualise the practitioner's choices. These tests are discussed further in Section 3.6.1.1. It must be recognized that, like all modelling exercises, an LCI and hence the results of an LCA can only ever be an approximation to reality and there is always room for improvement. It is still essential that assessments and modelling activities such as this are carried so that our understanding can be continuously, however iteratively, improved.

3.5 IMPACT ASSESSMENT

The *impact assessment* then takes the LCI model through, at least, the following two stages:

Classification: all the identified inflows and outflows are grouped together under a set of impact categories. For instance, the emission of both carbon dioxide and methane will be classified as contributing to climate change. Many outflows will potentially contribute to more than one impact, so the methodology has to prescribe a proportional allocation and must avoid double counting.

Characterisation: each impact category will be represented as a single representative inflow or outflow, so all of the inflows or outflows within each category are converted to a unit appropriate for that single representation. For instance, for the category of climate change the single representative outflow might be measured in 'kg of carbon dioxide', or kg.CO_2, so all the outflows classified as contributing to climate change, e.g. methane, nitrous oxide etc, would be converted to 'kg of carbon dioxide equivalent', or kg.CO_2eq. This is an extremely useful stage as the assimilation of classified flows into one representative unit enables rapid and, relatively, objective identification of impact cost and/or benefits for decision making purposes. However, as always, there are uncertainties. Whether a given inflow or outflow contributes to an environmental impact at all is usually still a matter for research, let alone the magnitude of that impact i.e. what actually is the climate change potential of carbon dioxide? Or of methane? Or, most importantly for characterisation, methane in terms of carbon dioxide equivalent? Hence, appropriate conversion factors are often updated and LCA study results will have to be updated accordingly.

These two stages constitute a full *impact assessment*, as set down by the International and British Standard (Standards Policy and Strategy Committee 2006). However, the following optional stages are also often carried out:

Normalisation: compares the characterised impacts to a reference 'normal' system and converts each result to a 'normalised score'. This process achieves two aims (Norris 2001):

- Assessment of the significance of the impacts within the context of a common reference system, typically a wider reference system within which the assessment subject exists. For instance, a subject product or service may appear to have a large impact in the category of fossil depletion and a small impact on natural land transformation, but without any context, it is difficult to say whether this is significant. If the impacts are normalised against, for example, the annual impact of an average European citizen (known as European person emission equivalents), it may be seen that because Europe has such a large impact on fossil fuel depletion per person already, the contribution from the subject product or service becomes negligible, whereas, what appeared to be a small impact on natural land transformation, becomes dominant within the context of total current natural land transformation per person across the whole of Europe.
- Conversion of all of the characterized impacts to a common unit. This means that the results can be compared more readily and the dominant impact type can be identified, in the normalized context. It also means that all the impacts of a single component, life stage or even whole product can be summed to give a single impact score.

These two outcomes are extremely useful for enabling effective results interpretation and dissemination so normalization is very commonly carried out. It must be born in mind, however, that this stage allows some subjectivity to influence the assessment, for example, what is an appropriate reference system? Inevitably, geographical and temporal bias will have to be re-introduced and justified. If an environmental impact is large in magnitude but small compared to the limited reference system selected, is it justified to regard it as 'negligible'?

The 2007 European average(Goedkoop, Oele, et al. 2010) was used for the 'normal' system throughout this work and "*people emission equivalent*" approach was adopted for the normalised impact scores presented in this thesis. This is determined by(McManus, Hammond and Burrows 2004):

$$\frac{Total\ European\ Output\ in\ Each\ Emission\ Category}{Population\ of\ Europe} = European\ Emissions\ per\ Capita$$

$$\therefore \frac{Emissions\ from\ the\ Process\ Studied}{European\ Emissions\ per\ Capita} = People\ Emission\ Equivalents\ (or\ Normalised\ Impact\ Score)$$

where the population of Europe is assumed to be 464,036,294 citizens (Goedkoop, Oele, et al. 2010).

The implications of this approach should not be overlooked. This study is focused on the UK electricity generation system, and as such there is an argument for using a UK orientated normalisation method. However, as the concerns of environmental stability are global, the reference system should perhaps be less rather than more geographically specific. Furthermore, what are the limitations of using the 'current' European average? Should 'normal' really be the baseline year of 1990 as implied by the reduction targets, or should it, in fact, be the future condition that it is hoped will be achieved by 2050? Investigating the consequences varying the reference system is outside the scope of this research project and is listed in the areas identified for further work in the concluding chapter to this thesis, see section 11.1.3.

Weighting: adjusts the normalised impact scores according to the perceived importance of the impact. This is useful if the results are only used within a community where the relative importance of environmental issues have been established and it is expected that any data disseminated on a product or services reflects the community's opinion. However, this stage, by definition, introduces a very high level of subjectivity and is prohibited in an ISO standard assessment. Explicit weighting was, therefore, excluded from the results presented in this thesis. However, the technique of summing the normalized scores to obtain a single overall impact score (or environmental burden) was used prolifically. This approach does, in fact, inherently imply weighting by its lack of weighting, i.e. it implies that all impact results are equal. This is not necessarily so for two reasons:

- Rightly or wrongly, some impact types are seen as more important than others. Specifically, the UK government and the Transition Pathways consortium (which provide the motivation for the work presented in this thesis) prioritise GHG emissions over any other impact type. As such, characterised results for this impact type were interpreted in isolation.
- The level of scientific certainty linking any given environmental flow to an impact varies. Hence, it is sometimes appropriate to eliminate results for categories where the characterisation factors are less extensively tested. In this thesis, results for the category of natural land transformation in the CHP case study were sometimes excluded so that the other results could be considered more closely.

These reservations do not, however, detract from the very powerful reason to use a single overall score i.e. that it allows a dense set of impact results to be summarised into a flexible, representative value. A single value not only enables quick and clear comparisons but it is essential in order to present environmental data in terms of established analysis metrics, such as displaced payback, which is explained in detail in Section 3.6.3.1. Using these established metrics is important in order to disseminate the results to a wider spread of the academic community as a knowledge of the specific environmental impacts is no longer required. Hence, total normalised impact scores are used, without any further caveats, in the analysis presented in this thesis.

Due to the complexity of the *impact assessment* phase, many practitioners will opt to apply a commercially available *impact assessment* methodology. The three existing *impact assessment* methods that were used for the case studies presented are discussed below.

3.5.1 RECIPE

The ReCiPe 1.01 methodology (Goedkoop, De Schryver, et al., ReCiPe 1.01 2008) was released in 2008 following a collaboration of RIVM, Radboud University, CML and PRé Consultants; their initials making up the capitalised letters in the methodology name. The method is largely a combination of the pre-existing Eco-indicator 99 (Goedkoop and Spriensma, Eco-indicator 99 1999) methodology and CML method (Guinée, Handbook on LCA 2002). This is the methodology most typically used in contemporary LCAs so it was adopted in order to aid dissemination of the work.

The ReCiPe methodology enables the assessment of an inventory and can generate characterised, normalised and weighted results in line with the general method explanation provided in Section 3.5. The fate analysis that is used to translate an inventory flow to a characterised result is specific to each impact category and is described in detail in the supporting information report published by the Dutch Ministry of Housing, Spatial Planning and Environment (Goedkoop, Heijungs, et al. 2009).

3.5.1.1 Midpoint versus endpoint

The CML method gives quantitative impact results using SI units, e.g. kg.CO_2eq or m^2 (of land use). The Eco-indicator 99 method gives predictive damage impact results. The most notable development in the ReCiPe methodology was the 'harmonisation' of these quantitative and predictive approaches, known as 'midpoint' and 'endpoint'.

At the midpoint, environmental inflows and outflows are characterised under one of the following 18 impact categories:

- Climate change
- Ozone depletion
- Human toxicity
- Photochemical oxidant formation
- Particulate matter formation
- Ionising radiation
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion
- Metal depletion
- Fossil depletion

A brief explanation of each of characterisation factors used to calculate the representative impacts for each of these categories can be found in Appendix B.

At the endpoint, the midpoint categories are further aggregated to into the following three damage categories:

- Damage to human health
- Damage to ecosystem diversity
- Damage to resource availability

This 'aggregation' process results in either: combining, separating or excluding midpoint categories. For instance, marine eutrophication and water depletion are excluded because of the extreme difficulties associated in translating the impact into a realistic estimate of damage. Fossil depletion and metal depletion are combined under the endpoint category of damage to resource availability. Climate change at the midpoint level has a range of potential damages and is split between damage to human health and to ecosystem diversity. Figure 5 provides a flow diagram of how the classified greenhouse gases are characterised to from a single midpoint impact and then aggregated to form to separate damages; to human health measured in DALYs (Daily adjusted life years) and to ecosystem diversity measured in species loss.

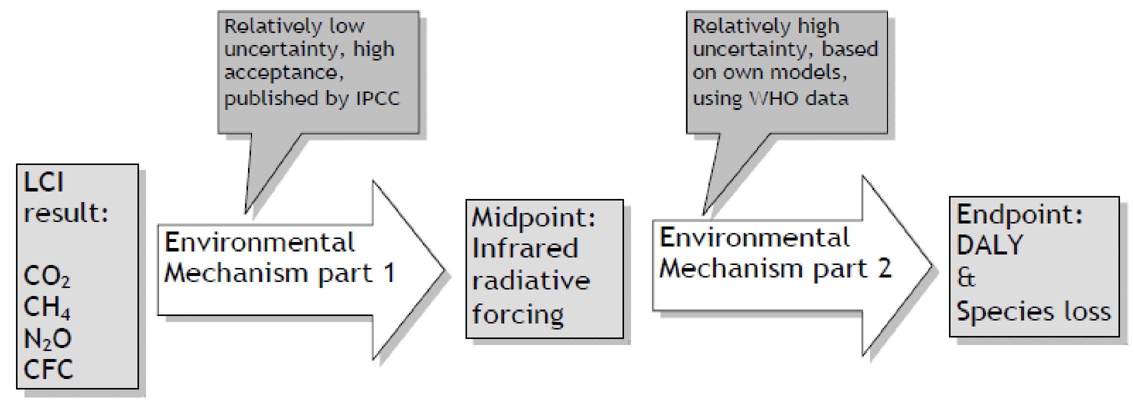


Figure 5 Visualisation of midpoint to endpoint aggregation for midpoint impact category 'Climate Change' (Goedkoop, Heijungs, et al. 2009)

The process of aggregating midpoint results to endpoint, introduces a level of subjectivity and uncertainty into the assessment as the potential for damage associated with any of the characterised inflows or outflows is disputable. The endpoint approach retains only those categories where potential damage can be predicted with more certainty or, perhaps moreover, where a greater amount of scientific research has been carried out, e.g. fossil fuel depletion and climate change. If there is little variation in the products being compared, the results may yield the same conclusions irrespective of which analysis approach is adopted. However if there is a significant variation in the nature of the environmental impact, different conclusions may be drawn depending on the approach adopted. The endpoint approach is often favoured in industry and in government as it puts seemingly intangible results into a 'real world' context. However the midpoint approach is typically favoured in academic studies as it avoids attempting to predict the future. As such, only the midpoint results were considered for the work presented in this thesis.

3.5.1.2 Cultural Perspectives

The Eco-indicator 99 (Goedkoop and Spriensma, Eco-indicator 99 1999) methodology introduced the option to select a 'cultural perspective' which helps to incorporate some of the uncertainties associated with translating measurable inflows and outflows into impacts, and potentially also damages. The ReCiPe (Goedkoop, De Schryver, et al., ReCiPe 1.01 2008) methodology retains this option. There are five archetypes distinguished by Cultural Theory (Thompson, et al. 1990). Figure 6 below shows the five archetypes and indicates how the value systems of each are influenced by the relationship with a group.

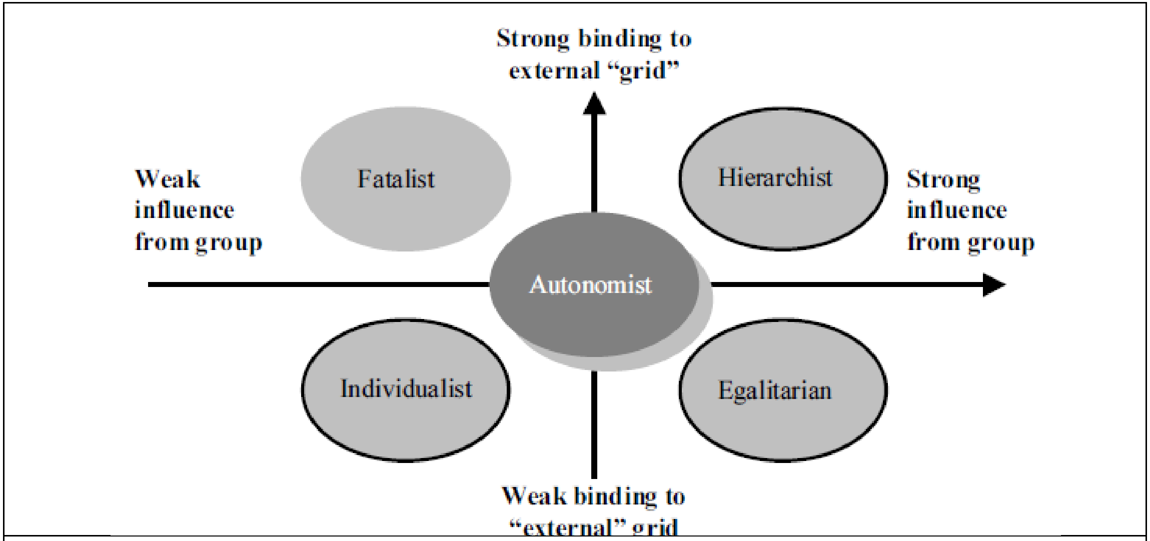


Figure 6 Visualisation of the five archetypes defined by Cultural Theory (Goedkoop, Heijungs, et al. 2009)

The concept of cultural perspectives was first applied to the problem of subjectivity in LCA modelling by Hofstetter (Hofstetter 1998). The ReCiPe (Goedkoop, De Schryver, et al., ReCiPe 1.01 2008) method allows for a choice of the following three cultural perspectives, which are identical to those in the Eco-invent 99 methodology (Goedkoop and Spriensma, Eco-indicator 99 1999):

- Individualist, '…we choose to include only proven cause and effect relations, when we have the choice we will use the short-term perspective.'
- Hierarchical, '…we choose to include facts that are backed up by scientific and political bodies with sufficient recognition.'
- Egalitarian, '…we consistently use the precautionary principle. We try not to leave anything out and if in doubt we include it...'

Applying the cultural perspectives does allow some flexibility whilst maintaining a convention which is very important for a credible methodology. However, it does also add a complexity which can be wholly overlooked, even by other LCA specialists, at the point of results dissemination. For instance, when comparing the results of separate LCAs, ideally it should be ensured that those results assume the same cultural perspective. This is not always possible as the perspective adopted is rarely reported. However, on the scale of possible variation in application, the choice of cultural perspective is unlikely to cause the largest difference in results. The hierarchical approach is most in line with the scientific and academic community so was adopted throughout the results presented in this thesis.

The most recent version of the ReCiPe methodology was used throughout the results presented in this thesis, that is version 1.05 (Goedkoop, De Schryver, et al., ReCiPe 1.05 2010) which was released in 2010.

3.5.2 IPCC 2007 GWP

The IPCC 2007 GWP, global warming potential, method is the method used by all versions of ReCiPe (Goedkoop, De Schryver, et al., ReCiPe 1.01 2008)(Goedkoop, De Schryver, et al., ReCiPe 1.05 2010) to classify and characterise the contribution to climate change at the midpoint. It was developed by the International Panel on Climate Change and classifies the global warming potential of the main greenhouse gases and characterises them with respect to carbon dioxide (measured in kg.CO_2eq). There are a range of IPCC methods that assume climate change factors with a timeframes of either 20, 100 or 500 years, denoted GWP 20a, GWP 100a or GWP 500a respectively. The 100 year timeframe is adopted for this study. As the method is a 'single issue' method, i.e. the only impact considered is GWP, or climate change, it is possible to compare products or systems without an intrinsic normalization stage.

3.5.3 CUMULATIVE ENERGY DEMAND

The Cumulative Energy Demand (Frischknecht and Jungbluth 2003), or CED, method is based on EcoInvent (EMPA 2007) data and was developed by PRé Consultants. CED is also a 'single issue' assessment methodology as it focuses on the life cycle energy demand alone. The characterised unit for all categories is MJ equivalent, although characterisation in its full sense is not really required as all relevant inflows are, by definition energy. There is also no need for an explicit normalisation stage. The method classifies energy demand into the following 5 categories:

- Non renewable, fossil
- Non renewable, nuclear
- Non renewable, biomass
- Renewable, wind, solar and geothermal
- Renewable, water

Further detail on these impact categories can be found in Appendix B.

The last two categories refer to energy directly generated by natural processes. This is not an energy resource that is being 'consumed' in the same way that other fuels are. This is not simply referring to their capacity to renew: biomass can be renewed but the energy required to produce it could be diverted for use elsewhere, and so is 'consumed', in a way that the motion of the wind or the heat/power of the sun could never be. Hence it becomes debatable whether this energy is truly 'sequestered' according to the definition of energy analysis given in Section 2.5.1. If the purpose of the LCA study is to simply establish the total energy demand over a product's lifetime, then there is a strong argument for including all energy, regardless of resource category. However if, as is the case with the case studies carried out for this thesis, the purpose is to determine the energy demand of an energy generation technology, then it becomes unwieldy to include energy of this sort. Analysis of this type is analogous to analysis in economics; if the energy resource cannot be otherwise invested then it cannot be truly seen as 'capital' and, hence, should not be included in the total energy investment against which energy 'returns' are compared. This seems intuitive for renewable technologies; for instance, in the case of a tidal barrage, it would be impractical, to say the least, and unhelpful for decision making to include the energy provided by the tide that turns the turbines, so it follows that, if this is excluded, any natural energy demand in the up or downstream processes should also be excluded. If this approach is adopted for renewable, then it must be adopted for all energy generating technologies. Hence results generated for these two categories are excluded from energy analysis carried out in this thesis.

3.6 RESULTS INTERPRETATION

The initial results of the *impact assessment* may initially be used to refine the *goal and scope* but should, almost, always be used to test the robustness of and iteratively improve the LCI.

3.6.1 INVENTORY ROBUSTNESS

The initial results will almost always reveal areas where improvements to the LCI can and/or should be made. Comparisons with results from studies completed on similar subjects will aid the identification of areas for inventory improvement and/or justification of the inventory choices made. Often, sensitivity testing will be required for the same ends.

3.6.1.1 Sensitivity Testing

Sensitivity tests involve trialling alternative inventory entries to assess the sensitivity of the overall result to the inventory choice. Sensitivity tests should be applied where:

- there is significant uncertainty as to the representativeness of the inventory data
- areas have been shown to have the greatest impact and hence significance to the overall result

If the overall result is significantly sensitive then further research should be carried out to ensure that the inventory choice is robust. If however, it is shown that the result is not sensitive then a decision to not iterate the inventory further is justified.

Once a satisfactorily robust LCI has been developed and an estimate of the environmental impact of the subject has been generated, the final results can be used to:

- estimate the overall environmental impact of the study subject and identify areas where environmental improvements are most needed or can be made most easily
- in the case of energy generating technologies only, calculate simple energy analysis metrics to test the abstract viability of the study subject
- compare the study subject with an alternative good or service to test the contextual viability of the study subject

3.6.2 SIMPLE ENERGY ANALYSIS METRICS

In the case of an energy generation scheme energy analysis metrics which are analogous to economics, as mentioned above, can be used to test the viability of the scheme. Investment and return, or ‘energy in’ and ‘energy out’ can be compared in the following meaningful ways:

3.6.2.1 Energy Gain Ratio

The energy gain ratio is the ratio of the total ‘energy out’ over a scheme’s lifetime to the ‘energy in’. It provides an easy metric for summarizing the lifetime energy efficiency of generation technologies. The energy gain ratio is given by the following equation:

$$\frac{Total\ Lifetime\ (Useful) Energy\ Generation}{Total\ Life\ Cycle\ Energy\ Demand\ (or\ Energy\ 'Sequested')} = Energy\ Gain\ Ratio$$

3.6.2.2 Energy Payback Period

An economic analysis may seek to predict how long a given scheme has to run in order that the financial return equals or ‘offsets’ the investment. In a similar way, an energy analysis will can predict the length of time that an energy generation plant will have to operate so that the total energy generated might offset that of the plants energy demand. The energy payback period tells us the point in the future when the installation will truly generate an energy benefit. It is also sometimes called the *Point of Futility* or *Breakeven Point*. The energy payback period is calculated using the following equation:

$$\frac{Total\ Life\ Cycle\ Energy\ Demand\ (or\ Energy\ 'Sequested')}{Annual\ (Useful) Energy\ Generation} = Energy\ Payback\ Period\ (yrs)$$

However, these metrics can only be applied to energy as other environmental impacts are not analogous to economics in this way, i.e. there is no return on investment when considering GWP or even fossil fuel depletion. Furthermore, the energy analysis of a single scheme will not necessarily assist in any 'real world' decision making. Taken ad absurdum, the most energy efficient thing to do is to do nothing. However, general opinion is that it is necessary to generate some electricity and some heat somehow. Hence quantitative comparison with alternative options and calculation of associated metrics, while slightly more complicated, can be more instructive.

3.6.3 USING COMPARISONS

A comparison can serve to put the impact of the subject product or service into an understandable context or to aid decision making between multiple options. For energy generation technologies, the energy analysis metrics described can be used to compare options very simply. For instance, the value of a novel electricity scheme is commonly tested by comparing the energy payback period and/energy gain ratio with that of a 'conventional' electricity scheme, e.g. a coal fired plant. Or, particularly in the case of heat from primary fuel, the optimum technology solution can be investigated by comparing the energy gain ratios and payback periods for the same scheme using different fuel types or for different schemes given the same amount of the same fuel. However, in order to compare alternatives by another impact category, or even just energy demand, the subject and alternative *impact assessment* results must first be resolved to an appropriate functional unit, as described in the *goal and scope*. Then the impact per functional unit can be directly compared. This can indicate the 'best' option from a selection. Where a novel technology is being assessed with a view to displacing a conventional technology, the unit specific impact cost or saving can be calculated.

A valuable metric for expressing the relative impact of a novel technology over the conventional technology it displaces is a 'displaced payback period'.

3.6.3.1 Displaced Payback Period

A displaced payback can be applied to any technology that is designed to provide the same beneficial output as an existing technology but with a reduced impact. The first step to calculate the saving per functional unit in comparison to the displaced conventional technology, this is given by the following equation:

Impact of displaced technology (e.g. National Grid) per functional unit	-	*Impact of novel technology per functional unit*	=	*Impact saving per functional unit*

Then the time period that the plant would need to operate in order for the impact savings to off-set the total life cycle impact of the plant, given the assumption that the generating capacity would otherwise have to be met by the conventional technology used in comparison, can be calculated. This is the displaced payback and is found using the following equation:

$$\frac{Total\ Life\ Cycle\ Impact}{Annual\ (Useful) Power\ Output\ \times Specific\ Impact\ saving\ (i.e. per\ functional\ unit)} = Displaced\ Payback\ Period\ (yrs)$$

As can be seen, a displaced payback calculation is by necessity a comparative calculation, and therefore is immediately useful as information for decision makers.

3.6.3.2 Comparison Data for this Thesis

The primary focus for each case study was the impact per unit of electricity generated. Hence the important findings were the:

- impact savings available in comparison to the current and 1990 baseline National Grids that will be 'displaced' by the low carbon technologies under assessment
- the impact savings or costs against a hypothetical decarbonised future Grid, and hence the contribution that the subject technology can, or can't make to that future Grid mix

Comparison with the baseline year 1990 is particularly important for determining the contribution to the UK carbon reduction target. Comparison with the current and baseline Grids indicate the impact reductions that might be available 'now' from the studied energy systems. The comparison with potential future Grids are essential to understanding the role that the studied systems can play on the unfolding pathway into the future and thus go some way to indicating the real sustainability of the energy generated.

In order to draw out these findings inventories developed for the Transition Pathways Consortium project, first phase (Hammond, Howard and Jones 2013), were used for the necessary comparison. Section 2.6.1 and Appendix A of this thesis provides more detail of how the scenarios were developed. Table 1 shows the percentage technology mix used in the LCI for the power supply for each of the National Grid models.

	UK National Grid 1990, baseline	UK National Grid 2008	UK 2050 - Central Control V1.1	UK 2050 Market Rules - V1.1	UK 2050 - Thousand Flowers V1.1
Nuclear power	20%	13%	23%	17%	7%
Fossil fuelled power (coal, natural gas, oil)	78%	79%	0%	0%	0%
Fossil fuelled power with CCS (coal, natural gas)	0%	0%	26%	42%	29%
Wind power	0%	2%	28%	22%	24%
Energy from waste	0%	3%	0%	0%	0%
Biomass fuelled power	0%	0%	2%	2%	2%
Pumped Storage	1%	1%	1%	1%	1%
Hydro power	2%	1%	7%	6%	9%
PV	0%	0%	1%	0%	4%
CHP (natural gas)	0%	0%	5%	5%	6%
CHP (biomass)	0%	0%	7%	6%	19%

Table 1 Percentage technology mixes for inventories for the 1990 baseline, 2008 and three 2050 future scenario UK National Grid electricity supply (Hammond, Howard and Jones 2013)

The LCI developed by the Transition Pathway work was assessed using the two impact assessment methodologies adopted for this work. Table 2 gives the characterised impact results for the 2008 (which is representative of the 'current' Grid mix) and 1990 baseline UK National Grid and for the three Transition Pathways 2050 Grid mixes per MWh.

Impact category	Unit	UK National Grid 1990, baseline	UK National Grid 2008	UK 2050 - Central Control V1.1	UK 2050 Market Rules - V1.1	UK 2050 - Thousand Flowers V1.1
Climate change	kg CO_2eq/MWh(e)	812.2	560.4	87.5	111.8	96.5
Ozone depletion	kg CFC-11-eq/MWh(e)	0.0	0.0	0.0	0.0	0.0
Human toxicity	kg 1,4-DB-eq/MWh(e)	232.1	118.9	82.7	113.5	107.1
Photochemical oxidant formation	kg NMVOC/MWh(e)	2.2	1.2	0.6	0.9	0.8
Particulate matter formation	kg PM10-eq/MWh(e)	1.2	0.6	0.3	0.5	0.4
Ionising radiation	kg U-235-eq/MWh(e)	254.5	181.0	300.0	223.3	90.5
Terrestrial acidification	kg SO_2-eq/MWh(e)	4.3	1.9	0.8	1.4	0.9
Freshwater eutrophication	kg P-eq/MWh(e)	0.3	0.2	0.1	0.1	0.1
Marine eutrophication	kg N-eq/MWh(e)	0.2	0.1	0.0	0.1	0.0
Terrestrial ecotoxicity	kg 1,4-DB-eq/MWh(e)	0.0	0.0	0.2	0.1	0.4
Freshwater ecotoxicity	kg 1,4-DB-eq/MWh(e)	5.1	2.6	1.3	2.1	1.3
Marine ecotoxicity	kg 1,4-DB-eq/MWh(e)	5.1	2.7	1.4	2.2	1.4
Agricultural land occupation	m^2/MWh(e)	15.6	7.7	21.8	22.3	42.8
Urban land occupation	m^2/MWh(e)	4.8	2.5	1.5	2.2	1.7
Natural land transformation	m^2/MWh(e)	0.1	0.1	0.0	0.1	0.1
Water depletion	m^3/MWh(e)	3.6	2.9	2.6	2.5	1.4
Metal depletion	kg Fe-eq/MWh(e)	3.7	2.8	6.8	5.7	6.4
Fossil depletion	kg oil-eq/MWh(e)	230.5	181.7	84.2	127.5	92.0

Table 2 Specific LCA characterised impact results for the 1990 baseline, 2008 and three 2050 future scenario UK National Grid electricity supply (Hammond, Howard and Jones 2013)

Table 3 gives the energy demand, per energy resource category, for the five representations of the UK National Grid described above. All six resource categories are given here for completeness but, as justified above, only the first four categories were used in the results comparisons with the case study technologies.

Impact category	**Unit**	**UK National Grid 1990, baseline**	**UK National Grid 2008**	**UK 2050 - Central Control V1.1**	**UK 2050 Market Rules - V1.1**	**UK 2050 - Thousand Flowers V1.1**
Non renewable, fossil	MJ/MWh(e)	9 678	7 628	3 537	5 354	3 862
Non-renewable, nuclear	MJ/MWh(e)	2 639	1 878	3 117	2 319	940
Non-renewable, biomass	MJ/MWh(e)	0	0	0	0	0
Renewable, biomass	MJ/MWh(e)	40	22	984	875	2 406
Renewable, wind, solar, geothermal	*MJ/MWh(e)*	3	75	1 186	894	1 160
Renewable, water	*MJ/MWh(e)*	85	63	297	250	351

Table 3 Specific energy demand per energy resource category by life stage for the 1990 baseline, 2008 and three 2050 future scenario UK National Grid electricity supply (Hammond, Howard and Jones 2013) (to the nearest MJ)

These results contextualize the case study technologies, in the ways described above, but were also used in the inventories of both case studies. In the case of the CHP study, a small amount of power is required from the Grid for upstream processes, and a slightly greater amount when considering a bio-fuelled plant. However in the case of the Severn Barrage, the power required to operate the plant outside of generating hours is, in fact, the greatest contributor to overall impact. Thus, the impact of the Grid mix itself becomes a variable in the assessment of any individual technology and, consequently, assessment of the Grid is, itself, iterative. This is most important in renewable technologies where other operational emissions are minimal and, therefore, most significant in large renewable schemes that will last a long time, like the Barrage. This could, however, also be true for other large schemes, like hydro or geothermal, or any large enough array of wind or marine devices that has an annual demand over a long enough lifetime. In this way, this thesis also showcases the importance of the relationship between focused studies on individual technologies and over arching studies of the full Grid mix.

3.6.3.3 Limitations of Comparison

The thoroughness of an LCI is necessarily restricted by the *goal and scope* of the study i.e. by the level of detail required from the results and by the timeframe of the study. This is an important factor to bear in mind when comparing different studies. As with all modelling, it depends on the question you ask as to what type of model is developed so comparison will always be restricted and should be done so carefully and with an appreciation of the likely variations.

3.6.4 CARBON ANALYSIS

The focus of the UK reduction targets and of the Transition Pathways project is GWP or carbon intensity per unit of energy generated. The life cycle approach is slowly being realized as essential to estimating 'real' carbon intensity and, hence, examining the relative roles that different technologies can (or can't) play in pursuit of a low carbon UK. Furthermore, the need to draw comparisons with an evolving Grid in order to assess the contribution that any individual technology could make is becoming clear. The work presented utilizes work completed by the Transition Pathways Consortium and aims to inform its next stage. Hence specific attention is given to the interpretation of the GWP result over the other environmental impact categories.

Carbon analysis cannot be compared to financial accounting in the way that energy analysis can because carbon emissions, in this context, cannot be regarded as a resource in the way that money or energy can be. However, it is worth noting that as a carbon economy becomes established, the lifetime carbon emitted or 'carbon intensity' will come to correspond to an actual financial investment.

3.6.4.1 Roles in the low carbon future

The percentage savings that the specific carbon intensity of each technology can offer compared to that of the 1990 baseline Grid, taken from Table 2, was calculated as part of the results interpretation. This gives an initial indication of the technologies' viability on the pathway to meeting the reduction target. However, even if the specific emission figures meet or exceed the 80% reduction target, this may not be enough to earn a place in the 2050 low carbon ideal. As mentioned in section 2.3.1, it is likely that the electricity supply sector will have to achieve considerably better than the 80% reduction target to compensate for the heat and transport sectors where reductions are predicted to be much harder to achieve. Further to this, in the 'more electric' future, the National Grid will have to meet a higher power demand than ever before as well as the reduction target.

In the base year 1990, the UK electricity sector supplied 300 TWh of power, to the nearest TWh, (Her Majesty's Government 1995, Table 47) and actual reported greenhouse gas emission were 205 Mt.CO_2 (equivalent) (Office for National Statistics 2013, UK Emission Statistics. Table 3). This implies that in order to meet the UK target, the electricity supply network will have to reduce its reported emissions to at least 41 Mt.CO_2 (equivalent) in the year 2050, 20% of the reported emission figure for 1990. The reported emission figure, however, is not a full life cycle value so is very likely to be less than the values that would be required to make a fair comparison with the case study results. By multiplying the specific emission figure for 1990 provided by the Transition Pathways work, shown in Table 2 of this thesis, with the supply capacity, a total life cycle emission figure of 244 Mt.CO_2 (equivalent) can be estimated for the 1990 baseline year. Hence the life cycle emission target for 2050 is 49 Mt.CO_2 (equivalent).

The Transition Pathway scenarios suggest that supply capacity in 2050 could range from 385 TWh to 499 TWh, the Market Rules scenario having the highest supply capacity and the Thousand Flowers having the lowest (Transition Pathways: Technical Elaboration Working Group 2010).

In order to further investigate the potential role of the case studied technologies in the ideal low carbon future, the proportion of the likely supply capacity and of the target carbon emissions they would contribute was determined. If the former is greater than the latter then the beneficial role is further confirmed. Even though the target life cycle emission is the most appropriate choice for a 'like for like' and hence fair comparison, the target implied by the reported emissions was also used as this is a well established benchmark.

3.7 SUMMARY

Life Cycle Assessment, LCA, is a way to account for the environmental burden of a given product or service across its whole lifetime, from material extraction to manufacture to use to disposal or from 'Cradle to Grave'. It represents to 2 conceptual steps forward in that it: 1) considers the whole life time and 2) considers a suite of impacts.

The International Standard Organisation state that an LCA study should consist of at least (Standards Policy and Strategy Committee 2006):

1. Goal and scope
2. Inventory analysis
3. Impact assessment
4. Results interpretation

As is often the case with modelling, the LCA process will require iteration between these stages in order to generate a satisfactory study.

The impact assessment methodologies used in the case studies presented in this thesis are:

1. ReCiPe 1.05 (Goedkoop, De Schryver, et al., ReCiPe 1.05 2010), with results presented at the midpoint using the hierarchical perspective, across 18 impact categories
2. IPCC 2007 GWP(International Panel on Climate Change 2007), with a 100 year timeframe
3. Cumulative Energy Demand(Frischknecht and Jungbluth 2003), usually with natural energy resource category results excluded from the total

Results interpretations include estimates of the overall environmental impact of the study subject and, hence, identify areas where environmental improvements are most needed or can be made most easily. Simple energy analysis metrics were also used to assess the abstract viability of the case study energy generation technologies. Comparisons were drawn with alternative energy generation options in order to assess the contextual viability of the technologies, primarily against LCA findings generated by the Transition Pathways, first phase; that is against: the 2008 UK National Grid (which is representative of the 'current' Grid mix), 1990 baseline UK National Grid and the three Transition Pathways 2050 Grid mixes (Hammond, Howard and Jones 2013). The comparisons with potential future Grids are essential to understanding the role that the studied systems can play on the unfolding pathway into the future and thus go some way to indicating the real sustainability of the energy generated.

These results for the UK National Grid mix are also used in the inventories of both case studies. Thus, the impact of the Grid mix itself becomes a variable in the assessment of any individual technology and, consequently, assessment of the Grid is, itself, is shown to be iterative. In this way, this thesis also showcases the importance of the relationship between focused studies on individual technologies and over arching studies of the full Grid mix.

CHAPTER 4. INTRODUCTION TO MARINE POWER

"How inappropriate to call this planet 'Earth' when it is clearly 'Ocean'"

- Arthur C Clarke

4.1 IN THIS CHAPTER

This chapter provides a summary of the UK marine power potential, both in terms of the resource available and the technology development. It justifies the selection of the Severn Barrage tidal scheme for further assessment as it is the largest single scheme proposed and uses the most established technology. A brief summary of the history of the scheme, the arguments against it and previously completed carbon and energy studies is also given.

4.2 INTRODUCTION

As it is an island, the UK has a higher coastline to land area ratio than almost any other country in Europe, possibly in the developed world. It is predicted that UK waters contain around 50% of the total European tidal resource (Her Majesty's Government 2013, Wave and tidal energy). The Severn estuary in South Wales has the second largest tidal range on the planet (The Environment Agency 2013), second only to the Bay of Fundy, Canada (Bishop 2013). Exploiting these resources presents a significant opportunity for UK energy security and carbon emission reduction. Hence, establishing the feasibility of doing so is important in developing the UK energy strategy.

UK marine technology innovation is currently leading the global field. UK based systems, such as SeaGen (Marine Current Turbines Ltd 2013) and *Pelamis* 'sea snake' (Pelamis Wave Power Ltd 2013), are already having significant successes in their prototype stages. Investment in marine power may not only provide a possible solution for decarbonising the UK electricity supply and for national energy security but it may also it provide an opportunity to revitalize the engineering design and manufacturing industries. The UK could seize the chance to be a world leader in an emerging technology that could soon be in demand across the globe.

The largest UK marine resource lies in the tidal range in the Severn estuary. The idea of a barrage scheme to exploit the tidal range has been around since the 1920s (Spevack, Jones and Hammond 2011). A number of proposals have been put forward and assessments carried out since then. The most comprehensive proposal and assessment was completed by the Severn Tidal Power Group, STPG (Severn Tidal Power Group and the Department of Energy 1989), which provided the details of the 'Cardiff-Western' scheme, which is generally regarded as *the* Severn Barrage. This installation could supply 17TWh of electricity per year which is around 4% of the total UK power demand. Objection to the scheme is wide spread but is mainly focused on the ecological changes that could occur in the estuary, as discussed in section 4.6. In this way, like many renewable energy proposals on undeveloped sites, the Severn Barrage debate pits 'greens against greens' in arguing the balance of local ecological conservation against global environmental sustainability. In 2007, the Sustainable Development Commission, SDC, expanded on the work carried out by the STPG. Following this, the UK Government decided not to pursue implementation of any scheme in the estuary but did not preclude reconsidering in the future nor the option of a private company or consortium taking up the project. Concerns over the potential ecological damage may have been a contributing factor in the Government's decision. However the over-riding reason not to proceed is undoubtedly financial, see section 4.5.1.

4.3 MARINE POWER IN THE UK

The UK is regarded as a world leader in the development of marine renewable devices(Her Majesty's Government 2012, DUKES. para 6.59), despite not having yet commissioned a full marine power plant. Many of the leading wave and tidal stream devices, such *Pelamis* 'sea snake' (Pelamis Wave Power Ltd 2013), see section 4.4.2, and SeaGen (Marine Current Turbines Ltd 2013), see section 4.4.1.2, were developed in the UK and are significantly advanced in their development. To maintain its position as world leader, as well as to increase its renewable energy capacity and reduce its carbon emissions, the UK must continue concept development with some urgency and see technologies through to fully commissioned power plants.

In September 2009 DECC's Marine Renewables Proving Fund, MRPF, with a value of £22M, was introduced, and in December 2009 the award of grants to *Atlantis Resources Corporation, Aquamarine Power, Hammerfest Strøm UK, Marine Current Turbines, Pelamis Wave Power* and *Voith Hydro* were announced (Carbon Trust 2011). The UK Government's 'Marine Energy Action Plan 2010' focused on action required from 'key actors' in the industry such as Government Agencies, the Crown Estates, utility companies, investment companies, design and manufacturing companies and research establishments (Her Majesty's Government 2010, Marine Energy Action Plan. p 6). Significantly the document states that, "...*there is a clear case to support marine energy development*..." (Her Majesty's Government 2010, Marine Energy Action Plan. p 14) and that this is because of range opportunities it presents in terms of the magnitude of the available resource, the benefits to the national economy, low carbon electricity and energy security. The plan also states that 1-2GW of wave and tidal stream and 1GW of tidal range installed capacity could be achieved by 2020, irrespective of the development of the Severn Barrage, (Her Majesty's Government 2010, Marine Energy Action Plan. p 14).

In June 2011, the DECC launched the 'Marine Energy Array Demonstrator' scheme with a fund of £20m. The fund is specifically targeted at arrays made up of at least three devices using technology that already been tested at full scale (Her Majesty's Government 2013, Marine energy). The specification is an understandable progression from the MRPF. However, it precludes early stage technologies, as well as all non array installations, such as barrages.

The South West Regional Development Agency Wave Hub installation was completed in August 2010. This provides the exciting opportunity for prototype technologies to be connected to the mainland for research and development purposes. Funding is also available for firms who choose Wave Hub. *Ocean Energy Ltd* have been granted a licence to install the first device by the end of 2013(Wave Hub Ltd 2013) and have secured up to £1m funding in doing so (BBC News 2012). Figure 7 shows the location of the Wave Hub.

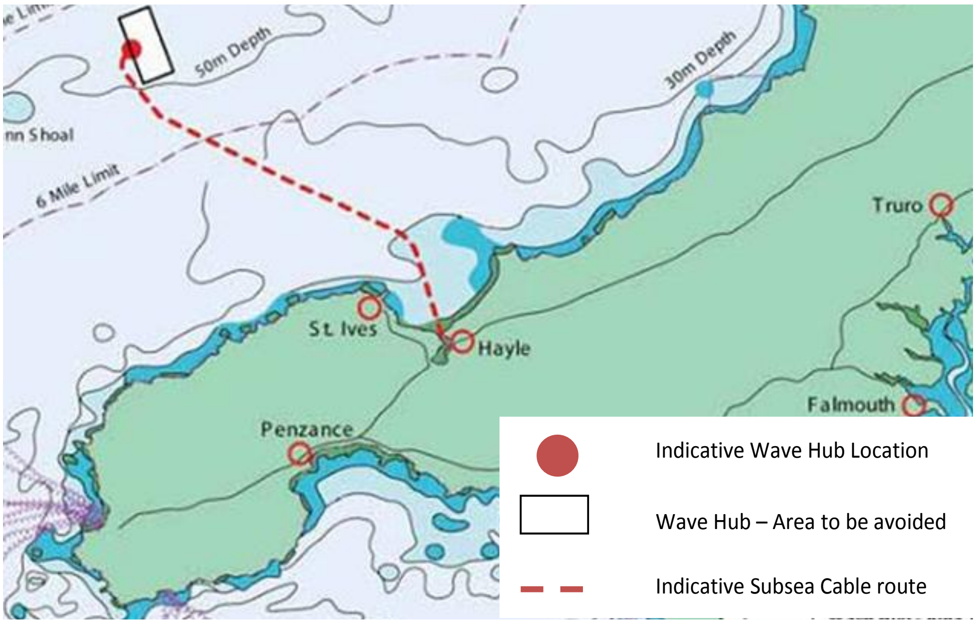


Figure 7 Location of SWRDA Wave Hub (Harrington 2011)

The closure of the Regional Development Agencies across the country and other so-called 'quangos', including the Sustainable Development Commission, does raise some concerns over the progression of UK marine power in the near future. These agencies were largely responsible for organizing the analysis required to assess the viability of schemes, providing the support and subsidy to developing schemes whilst having a responsibility to the public interest. Fears are that these roles will now either be privatized or not be carried out at all. In the former case the public interest may suffer as the pursuit of maximum profit is prioritized, as was the case with CHP in the '80s and '90s (see the later discussion in section 7.3), in the latter the marine energy industry may suffer, and hence so will UK industry and UK energy supply overall. A recent investigation carried out by the IMechE reports that despite its advanced position in technology development, UK low-carbon industry is, indeed, struggling to find sufficient private investment to support widespread implementation (Hargreaves 2013). The UK has previously stood at the forefront of wind energy development but a lack of investment, and possibly cultural impediments, meant that a 'flagship' design failed to emerge. Meanwhile, the Danish three-blade design and companies like *Vestas* proceeded to dominate the global market. Hopefully, UK private and public investors can learn from this recent history but given the current economic climate it seems an inopportune time to expect such a culture change. In short it seems that the UK possesses the technology and the resource to generate a substantial supply of marine power, however economic limitations are currently too restrictive to allow its potential to be realised.

4.4 MARINE POWER TECHNOLOGIES

Marine Power technology falls into two main types; those that harness the power of the tide and those that harness the power of the waves.

4.4.1 TIDAL TECHNOLOGIES

The stand out advantage of a generation technology that harnesses the tide is that the resource is highly predictable. It can be forecast with certainty what time of day and to with what range the tide will come in for years into the future. The disadvantage is that there is no easy way of making those predictable supply periods tally with demand periods, so Grid balancing, probably in the form of storage, will almost certainly be required. Predictions for UK tidal power capacity vary greatly, even within the DECCs information web pages (Her Majesty's Government 2013, Marine energy), however it can be estimated that the total UK tidal capacity is in the range of 28-40GW, which equates to approximately 16% of UK electricity demand or 245-351TWh per year. Figure 8 shows the peak tidal flow rates in UK waters, areas with fastest flow rates are shown in yellow through to the areas with slowest flow rates shown in dark purple. It can be seen that the fastest flow rates are where water is forced through or around land masses i.e. into estuaries, through islands or around peninsulas. High tide is not simultaneous across all of the UK coastline so the peak flows shown in Figure 8 occur at different times. One solution to the problem of supply side management for tidal devices might be to smooth supply using this natural staggering. This is discussed in more detail in later sections.

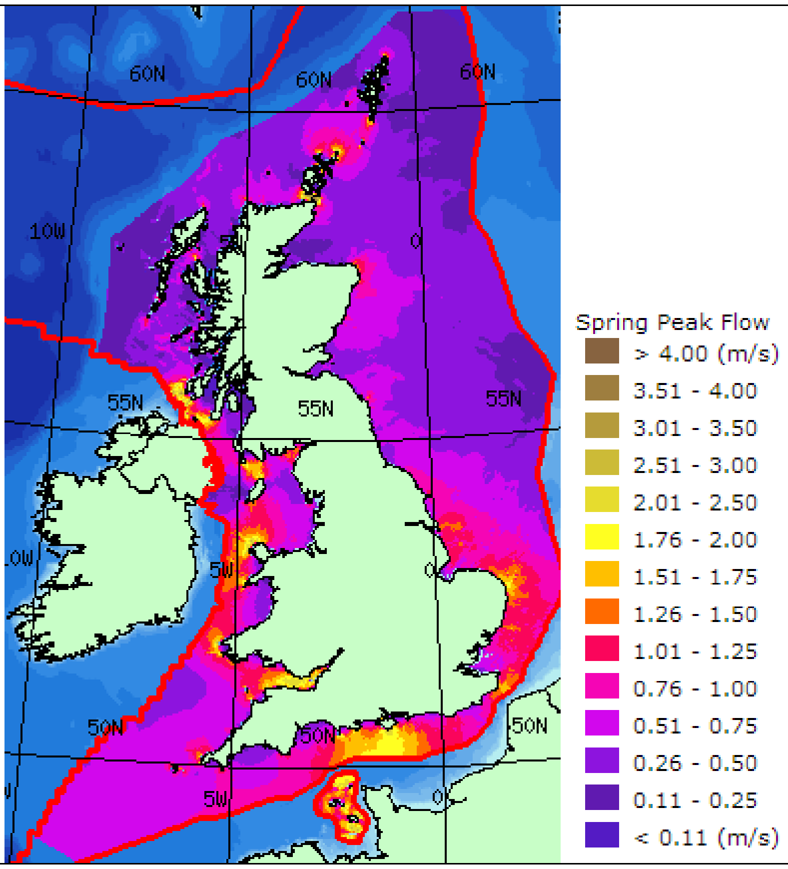


Figure 8 Map of UK tidal flow rates (Marine Environmental Research n.d.)

Tidal technologies fall into two further subcategories: tidal range, which typically exploit the head differential created in tidal estuaries, and tidal stream, which typically exploit high tidal flow rates through islands and around peninsulas. Tidal range energy provides the greatest proportion of the total tidal energy capacity, estimated at 219-263 TWh per year. Tidal stream is estimated at about 26-88 TWh per year.

4.4.1.1 Tidal range

Tidal range technologies exploit the head differential that can be created between a high tide level and a low tide level in an estuary. This can be done by constructing a barrage across the mouth of the estuary which creates a basin on the landward side of the barrage and delays the tidal extremes in the basin. When the tide on the seaward side of the basin ebbs, or 'goes out', sufficiently the head difference created means that water can flow from the basin to the sea, through turbines, usually, mounted in the barrage itself and generate electricity. Figure 9 illustrates this technology. The Cardiff-Weston Barrage scheme for the Severn Estuary, as described later in section 5.2, is an example of a tidal range scheme. Some barrage schemes have turbines that can operate in both directions so will also generate electricity when the tide is in flood, or 'coming in', but this can delay the high water level in the basin and hence reduce the ebb generation capacity.

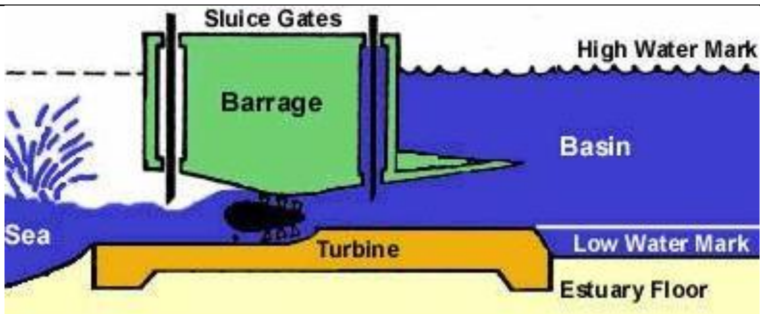


Figure 9 Tidal barrage operating in ebb generation mode (Lyon, Rayner and Jennings 1999)

An alternative tidal range system is that of tidal lagoons. Tidal lagoons are circular constructions which trap water in the lagoon at high tide and then, following the creation of a suitable head, generate electricity as the tide falls and water flows out of the lagoon through turbines mounted in the lagoon 'banks'. Tidal lagoon schemes are often considered less intrusive than barrage schemes because they are normally on a smaller scale and can be constructed further out to sea. Depending on the scale and proximity of the developments, it could be possible to implement a barrage and lagoon scheme in the same estuary, although it most likely that the schemes would reduce each other's output enough to make it uneconomical to do so (Sustainable Development Commission 2007, Turning the Tide. p 74).

Figure 10 shows the UK estuaries that have the highest tidal range and hence the most potential for tidal range application. Sites are more concentrated on the west side of Great Britain but there is a reasonable spread across all four compass points.

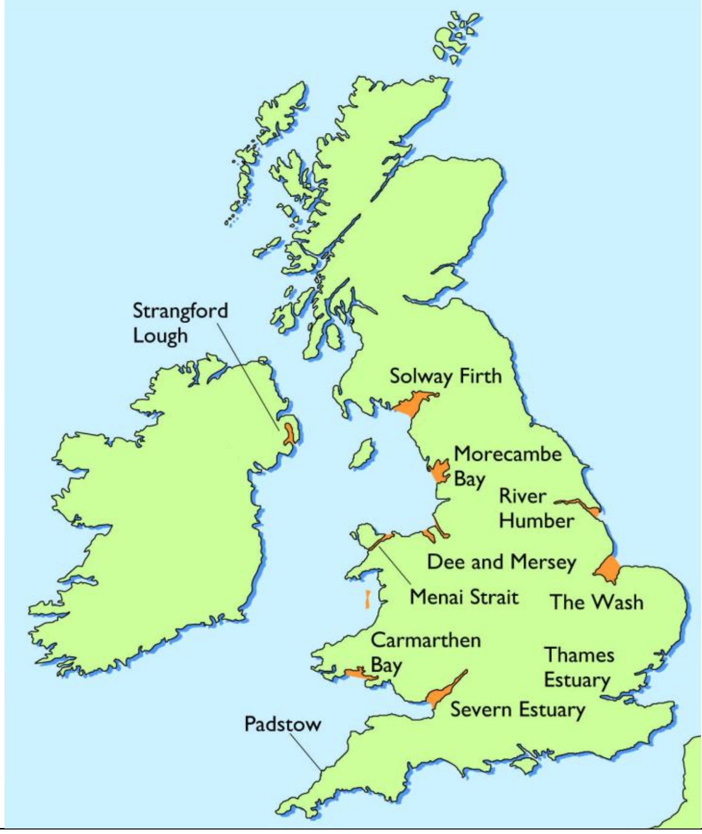


Figure 10 Map of potential UK sites for tidal range technology application (Open University 2004)

Figure 11 shows the tidal water level variation in nine of the sites shown over 24 hours on 11th September 2012 (BBC Weather n.d.). From this small selection, there does not appear to be any obvious correlation between tide times and estuary location, but it can be seen that tide times in different locations are disparate, demonstrating that there is scope for multiple schemes in multiple estuaries to supply a smoothed power input to the National Grid. One potential problem with this is that the acceptability of a barrage, or other tidal range, scheme in one estuary may rely on the provision of compensatory habitat for displaced wildlife in another (Sustainable Development Commission 2007, Turning the Tide. p 62), see section 4.6.1 for a specific discussion regarding potential ecological impacts in the Severn estuary. Hence, until the aspiration for sustainable energy significantly outstrips that for direct ecological conservation, the development of one site for power generation may necessarily prevent the development of another. Figure 11 also shows the magnitude of the available head in the Severn estuary over the other sites. The tidal range directly corresponds to the potential power capacity, so Figure 11 demonstrates why an energy scheme in the Severn estuary has become such a focal point for UK marine energy development.

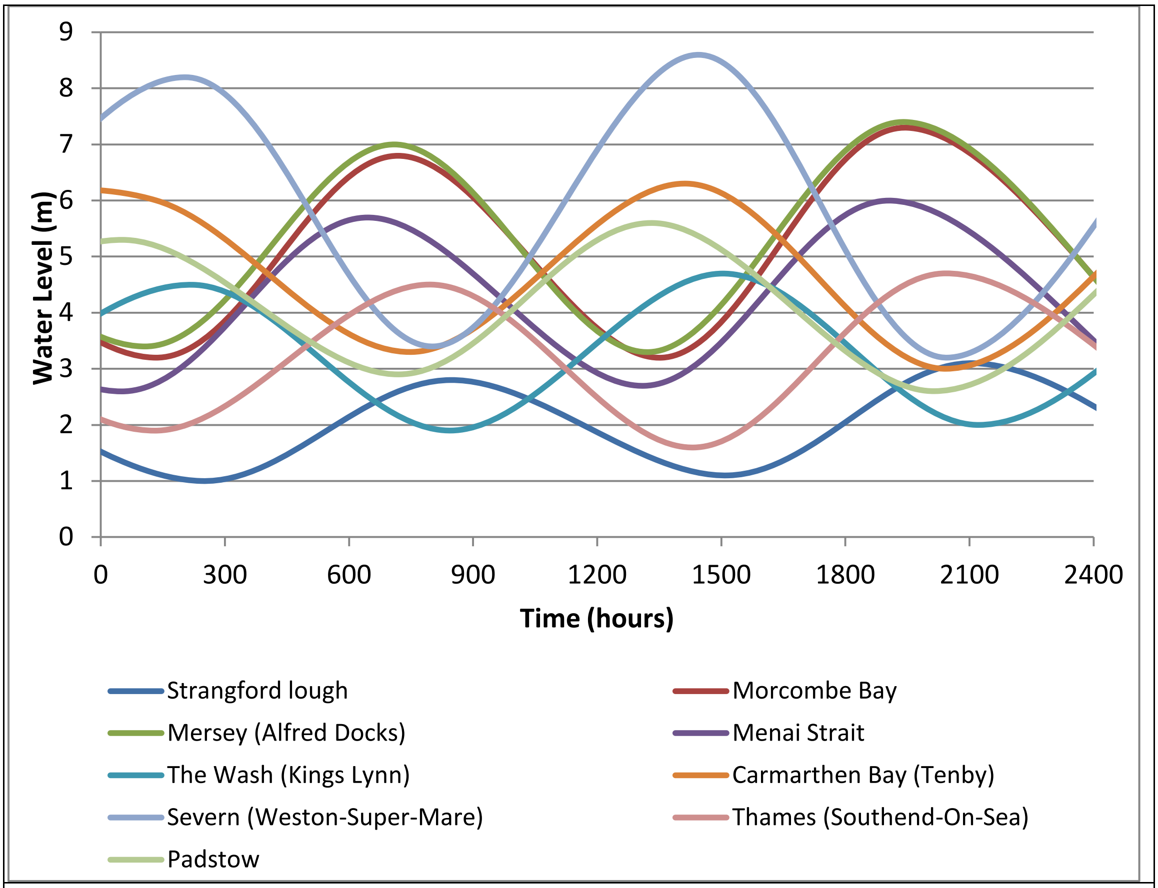


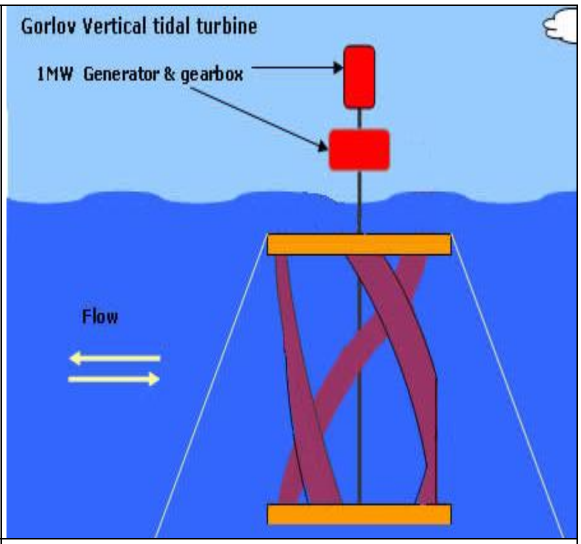
Figure 11 Tide profiles for 11th September 2012 across nine potential UK tidal power sites (BBC Weather n.d.)

Assuming that a maximum half of the energy capacity estimated for UK tidal range could be translated into electricity supply, i.e. that for every site developed a compensatory site of equivalent energy capacity must remain undeveloped, and taking the minimum estimate, it can be predicted that the total UK tidal range supply capacity is 110 TWh.

4.4.1.2 Tidal stream

Tidal stream technologies exploit the flow under the water surface generated by the tide. The resource is highly analogous to the wind, with the exception that tidal stream flow is highly predictable. Tidal stream devices are usually designed to be fixed to the sea floor and could be installed in arrays, like underwater 'wind' farms. The main types of device split into:

- Rotary motion: These are very similar in design to wind power devices. They can use aerofoil blades around an axis that is in line with the water flow (like the most commonly seen Danish style, three blade wind turbine) for instance the *Hammerfest Strøm* turbine shown in Figure 12; or the axis could be vertical to the flow, possibly using a helical structure, as employed by the *Gorlov* design shown in Figure 13; or horizontal to flow, like a *Gorlov* turbine on its side. Axial flow turbine designs are also sometimes 'shrouded' or 'hooded' in order to maximize flow speeds.

	
Figure 12 *Hammer Strøm* Tidal Current Turbine (OffshoreWind 2012)	**Figure 13 *Gorlov* Tidal Current Turbine (Climate and Fuel 1999)**

- Oscillatory motion: These devices use an aerofoil aligned either horizontally or vertically with the water flow to drive an arm up and down or from side to side. Figure 14 shows the 'Stingray' tidal device developed by *The Engineering Business*.

Figure 14 *The Engineering Business* Tidal Current Turbine 'Stingray'

Four out of the six devices awarded funding through the MRPF were 'in line', rotary motion tidal current devices. The remaining two were wave devices (Carbon Trust 2011), see section 4.4.2 for an introduction to wave power devices.

The most established model for a tidal stream turbine in the UK is the SeaGen type turbine, owned by the Bristol company *Marine Current Turbines Ltd*. The SeaGen is a rotary motion axial turbine. The first operating SeaGen turbine was installed in Strangford Lough in Northern Ireland in 2008. The first tidal stream 'farm' has been proposed for installation in the waters between the Isle of Skye and the Scottish mainland at Kylerhea. Figure 15 gives an artist's impression of what the tidal farm might look like.

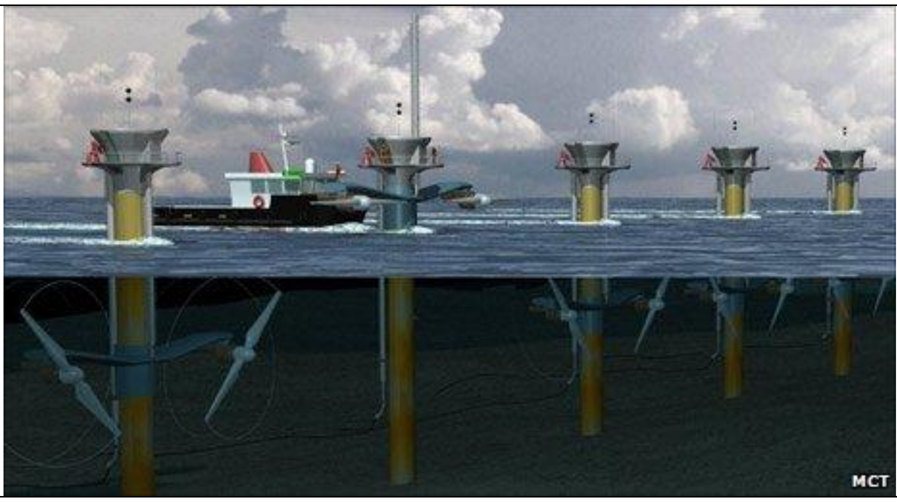


Figure 15 Artist's impression of MCT's SeaGen tidal farm proposed for Kylerhea (BBC News: Highlands & Islands 2011)

Figure 16 shows a map of those sites in UK waters that have the greatest resource for potential tidal stream application. It can be seen that these sites are different from those indentified for tidal range schemes, with the possible exception of the Somerset and North Devonshire coastline which leads into the Severn estuary. It is predicted, however that the exploitation of one type of tidal resource need not necessarily restrict the feasibility of exploiting the other. For instance, the installation of a Severn Barrage to exploit the tidal range is not predicted to affect the tidal stream resource further out to sea so a tidal stream farm off the South West coast of England could still be viable (Sustainable Development Commission 2007, Turning the Tide. p74).

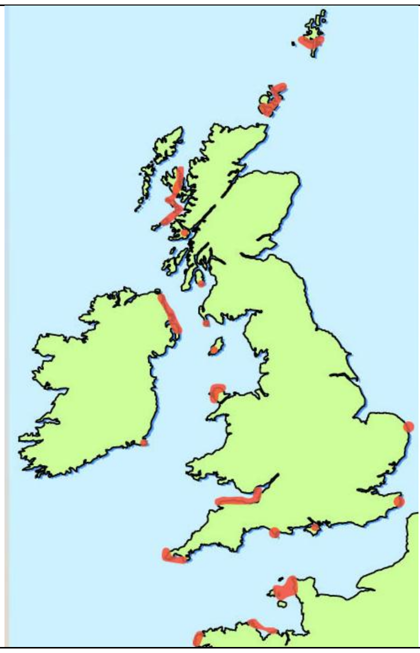


Figure 16 Map of potential UK sites for tidal stream technology application (Open University 2004)

It would seem more economically and ecological agreeable to commission several tidal current 'farms' around the UK coastline than several tidal barrage developments as they carry lower capital costs and are generally perceived as less intrusive on the marine environment. More research has been carried out into the feasibility of harnessing the tidal current power around the coast line in order to generate a more constant power output than into the same idea for tidal barrages. However it has been suggested that too many of the prime site located along the west coast are actually in phase to achieve a satisfactorily smooth output (Iyer, et al. 2012).

4.4.2 WAVE TECHNOLOGIES

As with tidal, predictions for the total UK wave capacity vary a good deal, but from the data available (Her Majesty's Government 2013) it can be estimated that it is also in the range of 28-40GW, so that also equates to approximately 16% of UK electricity demand or 245-351TWh per year. Figure 17 shows the annual mean wave heights in UK waters. The areas with the highest waves are shown in purple decreasing to the shortest in the green and blue. It can be seen that the further from the shore, the bigger the waves. Although exact wave heights are somewhat harder to predict than tidal water levels, sea waves could provide a steadier generating resource throughout the day.

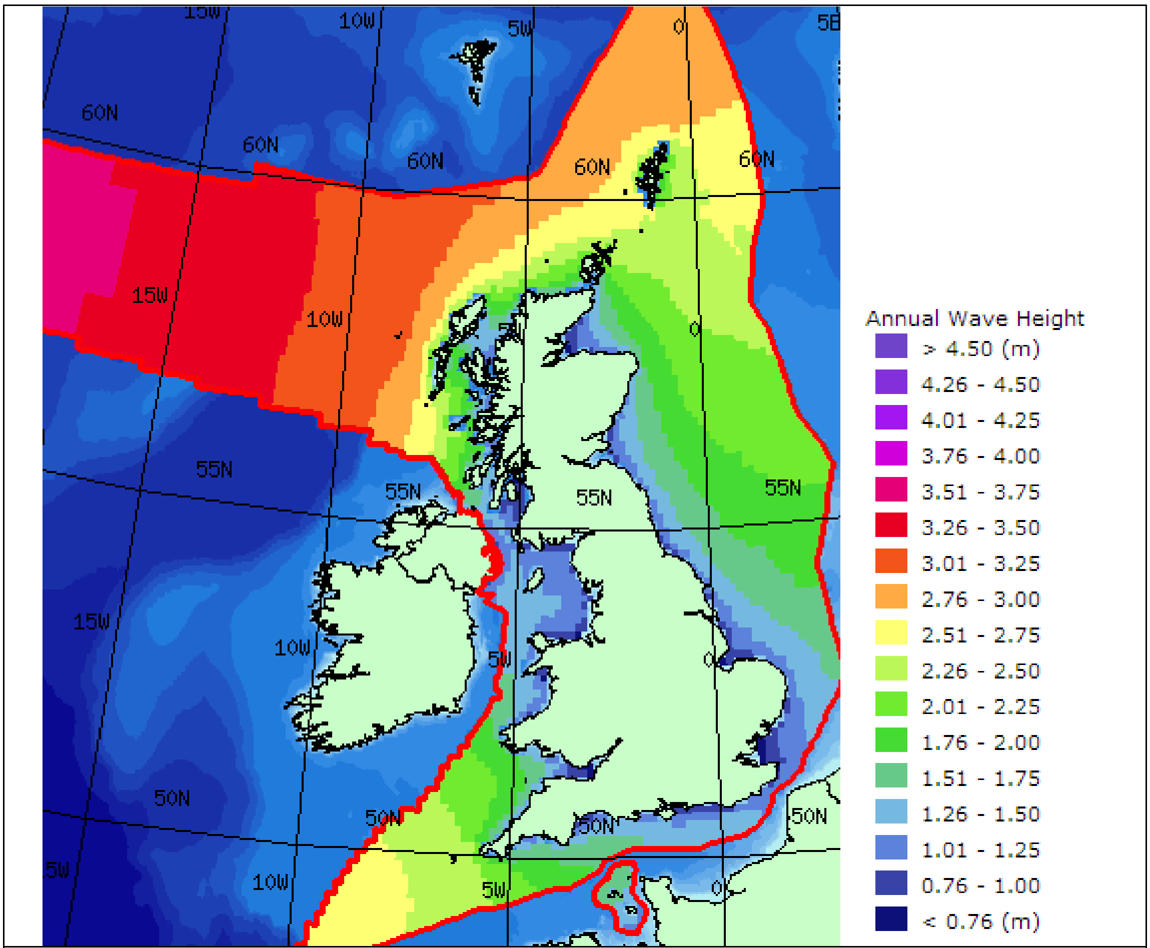


Figure 17 Map of UK annual mean wave heights (Marine Environmental Research n.d.)

One of the most prominent wave innovations is that of the UK based *Pelamis* device or '*sea snake*'. The *Pelamis* is a string of buoyant cylinders hinged together. As the waves pass along its length the sections flex relative to each other and pump up a hydraulic system, see Figure 18. Three devices, each 140m long (Lawn 2009), were successfully installed off the coast of Portugal in 2008 and had a generating capacity 2.25MW. The scheme was dismantled, however, due to the financial collapse of the parent company of the Portuguese utility company that had commissioned the installation (Pelamis Wave Power Ltd 2013).

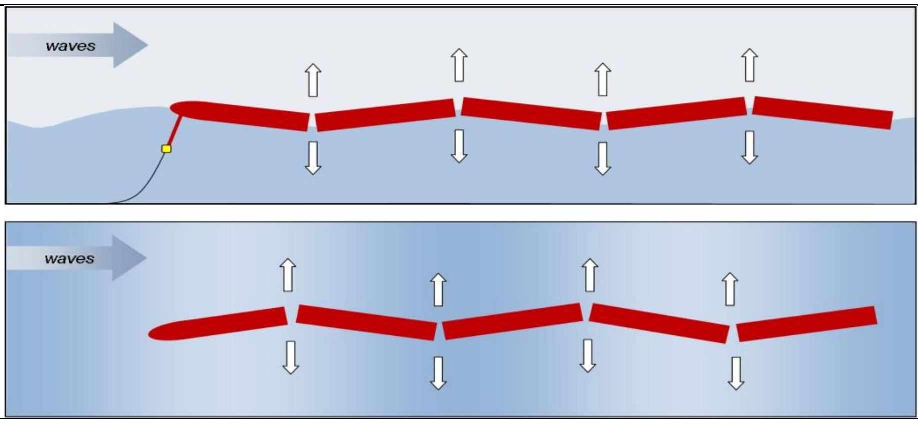


Figure 18 *Pelamis* Wave device(Pelamis Wave Power Ltd 2013)

There are many other designs for wave devices at various stages of development and this represents one of the most fertile areas for UK industry. However, it seems that investment in development has never been sufficient for any one device to become a success. Economic restrictions have limited wave energy development, as it has all marine energy development as discussed in 4.3. It may even be that the potential commercial benefits are acknowledged in the near future and investment increases, causing wave power to become a large contributor to the UK energy mix. However given the current lag in technology development and apparent lack of public or private funding available to further development this unfortunately, seems unlikely. Hence, as there are proven examples worldwide, a tidal barrage, specifically the Severn Barrage, was selected for further assessment.

4.5 THE SEVERN BARRAGE

The largest potential marine power scheme considered in the UK is the Cardiff-Weston barrage in the Severn estuary. The scheme would be a single, renewable installation and is predicted to constitute 4% of the UK electricity supply.

4.5.1 HISTORICAL BACKGROUND

The potential of the Severn estuary for energy generation was first explored when Lord Brabazon formed the first Severn Barrage Committee in 1925. They proposed an 800MW barrage at English Stones, which is the site of the more recent Shoots Barrage proposal but the committee disbanded in 1933 without undertaking any construction. In 1966, Électricité de France opened the world's first tidal barrage electricity plant in La Rance estuary in Brittany with an installed capacity of 240MW (The EDF Group n.d.). The barrage turbines at La Rance can generate in both directions, which means the plant will operate in both ebb and flood tides. It is generally thought that a substantial amount of ecological damage was caused during construction because of the aggressive techniques employed. There are very few subsequent reports on the technical performance of the plant and on the ecological effect in the estuary. However, it is at least certain that 47 years after its opening, it is still operating and is still the largest tidal power plant in the world. Meanwhile in the UK, a second Severn Barrage Committee formed under Sir Hermann Bondi in 1978. The Bondi Committee completed a report in 1981 which proposed a 7200MW ebb generation scheme to stretch from Lavernock Point near Cardiff to Brean Down near Weston-Super-Mare, with an annual output of 12.9TWh. The report confirmed the feasibility of this size of scheme but recommended further work (Department of Energy 1981). This was the start of the so-called Cardiff-Weston proposal, which is also commonly regarded as *the* Severn Barrage proposal. The Severn Tidal Power Group, STPG, was formed following the publication of the Bondi report in order to complete the recommended further work. The STPG published the results of an Interim Study in 1986 and it was again recommended that further work was carried out (Severn Tidal Power Group 1986). The STPG then carried out the Severn Barrage Development Project, funded equally by the STPG, the Department of Energy and the Central Electricity Generating Board. The STPG published the 'Severn Barrage Project Detailed Report' (Severn Tidal Power Group and the Department of Energy 1989), consisting of five volumes in 1989. This report remains the most comprehensive account of the proposed schemes and their feasibility with regard to the mechanical, electrical, economic and environmental constraints. The 1989 STPG report estimated that the average annual output from the Barrage plant would be 17.83 TWh and put forward a barrage design and bill of materials that has provided the basis of nearly all studies completed since.

As already discussed, the UK has been under increasing pressure to reduce its carbon emissions and increase its renewable energy capacity. As a Severn Barrage power scheme would represent a single high capacity, renewable, low carbon electricity plant, it attracted a renewed interest in the 2000s. In 2006 the Sustainable Development Commission began the first ever strategic overview of tidal power in the UK (Sustainable Development Commission 2007). The project assessed the technical, economical, social and environmental factors associated with barrage and non-barrage proposals for the Severn Estuary, however the majority of the technical study focused on the Shoots Barrage and the Cardiff-Weston proposals (Black & Veatch 2007). Analysis completed for the study estimated that the generating capacity of the Cardiff-Weston scheme would be 9GW, to the nearest GW, and the average annual power output would be 17 TWh, to the nearest TWh. This would constitute 4% of the current UK electricity supply and 0.6% of the current total UK energy supply (Black & Veatch 2007). The summary report states that a Severn Barrage would make a significant contribution to the UK's renewable energy targets but it expresses concerns over the possibility that a large, single development of this kind could detract from the need for a diverse range of decentralised technologies and consumer led energy efficiency (Sustainable Development Commission 2007, Turning the Tide. p 140). The report compares these concerns to ones expressed by the SDC with respect to nuclear power. These concerns seem rational, however scenario research has demonstrated that in order to achieve a sustainable energy future large scale, centralised schemes *and* decentralised generation and efficiencies will be required. To prevent one for the sake of the other seems a little idealistic. The SDC was firm in its opinion that measures would need to be taken to protect the public interest if a scheme were implemented and this could not be done via the private sector, the report foresees that,

> "*…taxpayers and consumers could end up with all the risks but none of the benefits*". (Sustainable Development Commission 2007, Turning the Tide. p 139)

With respect to ecological impacts, the report recommends that the Government undertakes an, "*...appropriate assessment...*". Despite these concerns however, the report recognises the importance of seriously considering the Severn Barrage and that states that the SDC is neither,

> "....*advocating unquestioning Government support for a barrage....*" nor would it, "...*suggest conditions that would effectively make its development impossible*" (ibid),

which is rather frustratingly inconclusive for such a long and costly study. The report provides a comprehensive set of recommendations but, essentially, it concludes that more investigation was required. The study omits any investigation or even discussion of how a barrage might in practice fit within a mix of technologies to make up a National Grid. Following the completion of the SDC project, the recommendations were submitted to the Government and the Department of Energy and Climate Change, DECC, launched a two year feasibility study in 2008. As part of the study, the DECC commissioned a Strategic Environmental Assessment, the results of which are discussed in Section 4.6. The conclusion of the DECC study, made public in 2010, in the midst of the continuing, so-called, 'economic crisis', which became truly apparent in 2008, was that there was no convincing case for any scheme at the current time. The Summary Report states that,

> "...*as a Severn scheme could not be constructed in time to contribute to the UK's 2020 renewable energy target, the case to build a scheme in the immediate term is weak.*" (Department of Energy and Climate Change, South West Regional Development Agency, Welsh Assembly Government 2010).

This conclusion rather draws attention to the short-term attitude of the Government that the SDC would, surely, strive to avoid. However, the outcome of the DECC feasibility study essentially reaches the same conclusion that the SDC report does, that,

> "...*many years of further detailed work would be needed to plan, finance and assess the impacts of such a large structure [...] before a case could be put forward for planning consent*" (ibid).

Although the report concedes that there are circumstances in which a future Government may choose to review the case, it was expected that a review would not take place before 2015 at the earliest. Hence it can be estimated that the earliest possible date that construction may begin would be around 2017, ready for full operation in 2025, although, given the history so far, this seems unlikely.

4.5.2 A PRIVATE CONSORTIUM: A NEW CHANCE FOR THE BARRAGE?

In December 2011, the private consortium Corlan Hafren, lead by Halcrow, submitted a business plan to the UK Government and put the Severn Barrage scheme back in the UK papers. Exact details of the scheme they propose are not publically available, but according to what has been published in the media (Barry 2012), the design will be predominantly similar to the STPG Cardiff-Weston Barrage with the following major differences:

- There will be just over 1,000 turbines rather than the 216 turbines in the STPG design. To make room for the extra turbines, 160 sluice gates will be removed and the span of the Barrage will be extended from 16km to 18km
- The Barrage will generate in flood as well as ebb mode. This will mean the scheme will reach peak output four times rather than twice a day, which, it is suggested, will help with grid integration and meeting demand.

- The scheme would operate with a much lower head than the STPG proposal. The maximum difference between the basin level and the sea level will about half that predicted for the STPG scheme, so approximately 3.5-4.5m rather than 7-9m. This would reduce the peak generating capacity and so would also help with grid integration.

No estimate of annual output of the new scheme has been made available. It has also not been expressly said anywhere whether the Corlan Hafren scheme still plans to include 'flood pumping', which is explained in detail in section 5.4.3.1.

In order for the Corlan Hafren scheme to begin, a 'hybrid' bill will have to be passed through government in order for the private consortium to build and own a scheme in a publically owned location, exploiting a publically owned resource. The Government is currently undertaking a public consultation, to which the author has submitted evidence (K. A. Kelly 2012). If the SDC had not been disbanded by the current government, then they might be able to reiterate their concerns that if such a scheme were privately owned then it could no longer for fill its potential as a public legacy and may well become a public burden. The end of the 1980s which saw the state left with the cost of decommissioning of the Magnox nuclear reactor plants that had been promoted so heavily by the Thatcher Government, demonstrates the potential consequences of privatised energy for the taxpayer. The precedent of private companies providing an expensive, and often sub-optimal, public service while, simultaneously benefitting from public subsidy is well established in the UK.

4.6 THE CASE FOR AND AGAINST THE SEVERN BARRAGE

Although the most recent 'moth-balling' of the Severn Barrage scheme is undoubtedly due to financial concerns, the most contentious issue since a scheme was first proposed is that of the effect on the local environment. The installation of the Barrage would cause considerable changes to the flow regime in the estuary and would raise the water levels on the landward side significantly above the current natural levels. These changes would have the potential to impact on the ecology of the area, on the levels of siltation, on the local flood risk and on the recreational activities that the site is well known for. The case study analysis completed and presented in this thesis is a traditional Life Cycle Assessment which cannot account for these types of environmental impacts. However, the following discusses the objections raised during the proposal consultation.

4.6.1 ECOLOGICAL IMPACTS

The Severn Estuary is wildly regarded as a unique environment and, as such, is protected under national and international conservation legislation. There are several Sites of Special Scientific Interest, SSSI, within the area which are protected by UK law. The area was recently awarded status as a Special Area of Conservation, SAC, and is therefore protected by the EU Directives on Birds and Habitats against biodiversity loss. It is included in the intergovernmental treaty, '*The Convention on Wetlands*' which was established in Ramsar in 1971, and is commonly known as the Ramsar Convention, to, "...*maintain the ecological character*..." of the named sites (UN Treaty Series No. 14583 1971). However these protections in themselves would not necessarily prevent development. Cardiff Bay had many SSSI, but the Cardiff Barrage and regeneration development went ahead. Reports on the anticipated effect on biodiversity are often positive, as will be discussed in more detail in this section. The Ramsar mission is the provision for "...*wise use of all wetlands [...] as a* *contribution towards achieving sustainable development...*" which is open to much interpretation.

The installation of the La Rance Barrage did have a substantial negative effect on the local ecology. However, the construction methods employed at La Rance were much more uncompromising than those proposed for a Severn Barrage, for instance the site was dammed and completely drained for construction. There are very limited reports on ecologically recovery. However a 40 year review suggested that the area was, in fact, more species diverse than it had been previously (Lalau 2009).

The two most significant effects of a barrage and their associated potential impacts have been identified as follows:

- Reduction in inter-tidal zones. The Barrage would significantly raise sea levels causing some intertidal habitats, including saltmarsh and mudflat, to be reduced in area and exposed for less time. These areas currently provide feeding grounds for diverse waterfowl populations (Sustainable Development Commission 2007, Turning the Tide. p 98).
- Reduction in sediment transportation. It is predicted that a barrage would affect sediment transportation by reducing the tidal force on both the basin and seaward sides of the barrage, resulting in deposition of high proportions of the mobile sediment load. This would bring about clearer waters and changes in the makeup of the sea floor.

Barrage proposals have been criticised extensively by environmental pressure groups because of the potential ecological damage and many maintain that alternative generation technologies would be a better solution for exploiting the power of the Severn tidal range. Friends of the Earth Cymru's belief is that,

> "*To destroy a unique, internationally important and protected conservation area to generate just one percent of the UK energy is not the way forward" and that, "...there are environmentally benign ways to generate tidal energy from the Severn estuary*" (Friends of the Earth Cymru 2010).

Following the Government decision to moth-ball the scheme, Dr Sean Christian, RSPB Cymru Head of Conservation, said,

> "*Climate change threatens an environmental catastrophe for humans and wildlife. Harnessing the huge tidal power of the Severn has to be right, but it cannot be right to trash the natural environment in the process*", (RSPB Cymru 2010).

It is not expressly clear what technology would be acceptable to local conservationists, but a lower head barrage, a smaller barrage further upstream or a tidal lagoon further out to sea would certainly reduce the area of saltmarsh and mudflat affected. No assessment data appears to have been published by these pressure groups and as such it is hard to interpret which specific ecological impacts they anticipate and based on what evidence. Also, it seems that although the consequences of climate change have been acknowledged there is little attempt to balance the benefits the Barrage could offer in this respect against the immediate environmental impacts.

As part of the 2010 feasibility study, the DECC commissioned a Strategic Environmental Assessment, SEA, which was carried out by a collaboration of environmental consultancies.

In the conclusion to their feasibility assessment, the DECC state that the scale of the predicted effect of the scheme would be, "...*unprecedented*..." in an environmentally designated area (Department of Energy and Climate Change, South West Regional Development Agency, Welsh Assembly Government 2010, Severn Tidal Power. p 5). The summary report anticipates that the reduction in intertidal zones, inclusive of potential mitigation measures, would be 40-50% and this would cause, "...*significant*...", reductions in 30 bird species (Department of Energy and Climate Change, South West Regional Development Agency, Welsh Assembly Government 2010, Severn Tidal Power. p 40). However, in a notable exclusion from the summary report, the individual topic paper on 'Marine Ecology' predicts that the clearer waters will lead to increases in macroalgae and invertebrate populations and diversity which will have,

> "...*significant positive effects for intertidal mud and sandflats*..." (Parsons Brinkerhoff Ltd; Black and Veatch Ltd; ABPmer n.d., Marine Ecology. p 14).

The topic paper also draws attention to the fact that climate change itself will bring about reductions in intertidal areas via sea level raises, and that current national and international conservation legislation does nothing to protect areas from this. Furthermore climate change is predicted to bring about increases in water temperature and acidity which would not be associated effects of barrage implementation (Parsons Brinkerhoff Ltd; Black and Veatch Ltd; ABPmer n.d., Marine Ecology. p 11). The paper also states that estuarine and coastal environments are already being altered because of additional flood defence measures being taken against the increased flood risk due to the effects of climate change (Parsons Brinkerhoff Ltd; Black and Veatch Ltd; ABPmer n.d., Marine Ecology. p 11). The carbon foot printing assessment carried out as part of the SEA, discussed further in section 4.7, actually includes the carbon reduction benefits of the sequestration service provided by the sediment deposits in its 'best case' calculation (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. p 97). The DECC summary report does not discuss any of the positives identified by the SEA and makes no attempt to balance the impacts of the Barrage against the impacts of climate change. In short, it would appear that the summary report is written in support of the decision not to proceed with development, which was largely based on economic factors and the public perception of ecological impacts, rather than a full reflection of the study findings.

The anticipated loss of habitat on the landward side and the effect that could have on bird populations does seem to be justified, however. Studies on the numbers of bird species in the neighbouring Cardiff Bay during and after the construction of the Cardiff Bay Barrage demonstrate that numbers have reduced and that provision of compensatory habitat did little to mitigate this, although it does not seem that whole species loss was observed (Burton, Rehfisch and Clark 2002) (Ferns and Reed 2008). However, Dr Rob Kirby, a marine expert who has studied the area since the 1970s has predicted that the increase in micro and macro organisms resulting from clearer, calmer waters would provide sufficient food source to ameliorate the loss in feeding area (Kirby 1988). Kirby holds the opinion that the Barrage could benefit the local eco-system and that those campaigners who believe otherwise hold its current condition in irrationally high regard. In 2005 he contributed to an environmental reappraisal of the estuary and concluded that the Severn estuary is, in fact, evolving towards a "...*barren system...*", and that is exacerbated by foreshore erosion, turbidity and areas of mud deposits that are actually expanding (Kirby and Shaw 2005). The installation of the Barrage scheme would reduce all of these effects and it is estimated that a barrage would in fact make the estuary more rather than less ecologically abundant

(Kirby 2010). Prolific publication on the same point does not necessarily strengthen the case, however there seems to be very little scientific publication to contradict Kirby. In fact, in 2010 a separate study supported the hypothesis that the Barrage would increase biodiversity both in the basin and in the channel, and proposed that that would lead in an increase in commercially fishing opportunities in the channel (Warwick and Somerfield 2010). Following the Governments decision in 2010, Kirby told BBC Somerset that he felt, "*…frustrated, amazed and angry…*", and he has been quoted as demanding,

> "*The idea for a barrage in the Severn estuary has been around since 1911, why are we failing again?*"(Cafe 2010).

4.6.1.1 Technical impacts of Sediment Deposition
The deposition of sediment could also have technical consequences for the Barrage itself. Sediment build up on the basin side could decrease or even cease plant operation. However, while this problem has the potential to render smaller schemes, such as the Shoots Barrage, unviable, it is estimated that it would not have that magnitude of consequence for the STPG Cardiff-Weston proposal (Sustainable Development Commission 2007).

4.6.2 FLOOD RISK
The installation of a barrage in the Severn estuary would lead to both positive and negative effects on the local flood risk, although the net result is hard to establish. The Barrage could provide enhanced protection from coastal flooding which is expected to worsen in probability and severity due to increased sea levels and larger storm surges as a result of accelerated climate change. However, the Barrage could lead to greater risk from fluvial and surface water flooding as it would raise the water level on the landward side and restrict the land and upstream tributary drainage function that the estuary currently provides. This could be mitigated, to an extent, by including upstream flood defences in the Barrage proposal. The cost of these additional defences was included in the cost estimates for each scheme in the 2010 review and longer-lasting protection provided could be a benefit of a scheme installation (Department of Energy and Climate Change, South West Regional Development Agency, Welsh Assembly Government 2010, Feasibility Study Conclusions and Summary. p 38). It is unknown what flood mitigation, if any is included in the Corlan Hafren proposal.

4.6.3 RECREATION
Tourism is reported to be one of the largest employment sectors in the Severn-side region (Sustainable Development Commission 2007). If the predicted negative impact on the local bird life came to fruition, this may impact on the number of ornithologists visiting the area. Furthermore, a barrage would prevent the world famous phenomenon of the 'Severn Bore'[2] and hence the associated surfing and other visitor activity would cease. However, it is proposed by both the STPG study and by the SDC that the reduction in tidal range and the calmer currents that result from a barrage installation may increase the potential for sailing, angling and other tourist seaside recreation (Severn Tidal Power Group and the

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[2] A 'bore' is a large surge wave that progresses along the length of an appropriately shaped estuary. There are around 60 estuaries in the world that can generate bore waves, and the Severn bore is one of the largest in the world (The Severn Bore 2012).

Department of Energy 1989)(Sustainable Development Commission 2007). In addition to this, experience at La Rance suggests that the Barrage itself would be a tourist attraction.

4.7 REVIEW OF EXISTING ENERGY AND CARBON ANALYSES OF THE SEVERN BARRAGE

The first comprehensive energy accounting study was completed by Roberts in 1982 (Roberts 1982) and was based on data provided by the, recently formed, STPG and other stakeholders. It employed two energy accounting methods. Where only a cash sum was available, then an appropriate cash-to-energy (MJ/£) factor determined using input/output methodology was applied; where actual quantities were known, process analysis methodology was used, the conversion factor then being MJ (or GJ) per tonne (Roberts 1982). Roberts' calculations consider three proposals, but they show that the scheme which is most similar to the Cardiff-Weston Barrage would have an energy ratio of 14:1 ±15%, based on an annual power out of only 12 TWh. Roberts concludes that,

> "...*a tidal barrage scheme on the Severn estuary would appear to be a very worthwhile investment*" (Roberts 1982).

The SDC report includes a short section on 'embedded' carbon which focuses on the construction stage (Black & Veatch 2007). Calculations are limited to the manufacture of the construction materials only, cradle-to-gate, and are based on information from the Inventory of Carbon and Energy, ICE, database (Hammond and Jones 2010). A final figure of 5 Mt.CO_2 is given for the overall carbon emissions of the Barrage. The sum of the emissions associated with material transport, gate-to-site, and site works are considered to be of a similar magnitude to those of manufacture. Operation emissions were expected to be very low compared with construction and no estimation of decommissioning emissions is made as this is considered too speculative. The report does highlight that this type of assessment is unusual as assessments of conventional, fossil fuelled generation technologies do not normally consider any construction emissions as these are minimal compared to operation emissions. Rather confusingly, section 4.2.3 of the report entitled, "*Energy payback for structure installation"* states that,

> *"The energy payback associated with the Severn Barrage can be calculated in relation to the amount of CO_2 that would otherwise be produced from using the energy that comes from the electricity grid*",

and then goes on to present, what appears to be, displaced carbon payback period calculations. This apparent confusion between energy and carbon metrics does not lend confidence but the displaced carbon payback calculation does appear to be correctly applied. Two displaced payback periods are given via comparisons with carbon emissions of: a) UK electricity grid generation mix and b) a combined cycle gas turbine are also presented in the report. The results are shown in Table 4. There does not appear to be even a discussion of the potential changes in the estimate against National Grid mix if the carbon intensity were to reduce by the time the Barrage is commissioned.

Average Annual Energy (TWh/year)	**17.0**
CO_2 emissions (gCO_2/kWh)	2.4
CO_2 emissions of National Grid Mix (gCO_2/kWh)	430.0
CO_2 saved wrt to National Grid Mix (gCO_2/kWh)	427.6
[Displaced] Payback period (months)	**8.2**
CO_2 emissions of CCGT (gCO_2/kWh)	329.0
CO_2 saved wrt to CCGT (gCO_2/kWh)	326.6
[Displaced] Payback period (months)	**10.7**

Table 4 Carbon Analysis Results from the SDC study (to 1 decimal place) (Black & Veatch 2007)

A Shawater Ltd study (Woollcombe-Adams, Watson and Shaw 2009) into the implications for carbon emissions of the Barrage focused almost exclusively on the embodied carbon of the Barrage construction materials. Based on the bill of materials established in the STPG work, the study estimates the carbon emissions of the material manufacture, or cradle-to-gate, and transport to site, gate-to-site. However the report does not make it clear how the assumptions for transportation methods or distances were made. The study assumes that 'on-site' works would emit less than 20% of the carbon associated with the construction materials, and that there would be no emissions in operation. Maintenance is also assumed to have no emissions, and this is justified by claiming that La Rance Barrage still operates with its original turbines. This seems overly simplistic as there would be at least a regular preventative maintenance schedule at the Severn Barrage, as there would be at any major engineering works and, in fact, it is reported that the turbines at La Rance were "...*renovated*..." after the first 30 years of operation and some of the components have been replaced (Lalau 2009). Decommissioning emissions are estimated to be less than that of construction, which is in line with other studies. It is claimed that the STPG annual generating capacity of 17 TWh is likely to be an under estimate and that it could be nearer 19 TWh, and it is proposed that using the lower estimate in the analysis "...*more than*..." offsets any discrepancy in the operation emission assumption (Woollcombe-Adams, Watson and Shaw 2009). No evidence is offered as to why the authors assume that output would be greater than that predicted by other studies. A displaced carbon emission payback period is calculated by comparison with the operation emissions only of the Drax coal-fired power station and concludes that this would be less than 6 months. This mismatch in life stages limits the usefulness of the study conclusions as it does not compare 'like-for-like'.

A University of Bath '*Technology Assessment*' of both the Cardiff-Western and Shoots Barrage proposals, includes an energy analysis, a carbon analysis and an economic investment appraisal (Spevack, Jones and Hammond 2011). Calculations are based on analysis of data provided by previously published literature with additional new data presented in order to improve the gate-to-site analysis of the construction materials. The study establishes likely suppliers and hence provides justified estimates for the likely transport methods and distances to site. The annual energy output is assumed to be 16.8 TWh, taken from the SDC study. Analysis of the energy consumption of the onsite construction activities consists of testing the Roberts' estimates by comparing them with alternatively derived estimates using either the ICE (Hammond and Jones 2010) or EcoTransit (Institut fur Energie und Umweltforschung (IFEU) 2008) databases. In general, the Roberts estimate is shown to be larger than the alternative and is therefore adopted, in line with the precautionary principle. An energy gain ratio range of 18:1 to 26:1 is calculated with an energy payback period of 8.6 years. Carbon emissions are extracted from the corresponding database for processes where the energy estimates are shown to be comparable to the Roberts' results; where they are not, the process is excluded from the carbon analysis. The Roberts percentage assumptions are adopted for calculations with respect to the operation and maintenance stages. In-line with other studies, decommission is excluded. A final specific carbon figure of 9.5-11.0 kg.CO_2/MWh is given. This study provides considerably more detail for the construction stage inventory, but the estimation methods used elsewhere offer little progression from the Roberts' study.

As part of the SEA commissioned by the DECC in 2010, a 'carbon footprinting' exercise was completed. The calculation adopted a life cycle approach and presents separate estimates for the construction, operation and decommissioning life stages. The construction is still reported to be the most impactful life stage at 14-28 Mt.CO_2, operation is reported at -20-14 Mt.CO_2 and decommissioning is estimated at 1-3 Mt.CO_2 (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. Table 5.). The lowest estimate for the carbon emissions for the operation stage is negative because it is inclusive of the potential carbon sequestration service provided by the increased sediment deposits caused by the Barrage (Parsons Brinkerhoff Ltd; Black and Veatch Ltd; ABPmer n.d., Marine Ecology. p 14). This was the only study so far that had expressly included any power demand for pumping in the operation inventory. However, the report does not state the assumed magnitude of the power demand for pumping and, as the study assumes that the plant operates in ebb mode only (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. p 12), it is unclear what the pumping is for. The carbon intensity of the power demand assumes that estimated by the DECC based on the assumption that all the policies in the '*UK Low Carbon Transition Plan*' are successfully implemented (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. p 107). This means that the estimates are an absolute best case scenario and also that they are 'point of production' rather than life cycle estimates (Her Majesty's Government 2011, 2050 Pathways Analysis. p 118). The Grid carbon intensity used was assumed to drop below any of the Transition Pathways values for 2050, Table 2 of this thesis, by 2039, to 80 kgCO_2/MWh. By 2049 the Grid intensity is as low as 20 kgCO_2/MWh (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. p 107). Hence, the emissions value calculated for pumping power demand will be the lowest possible estimate and arguably inappropriate for use in a study that claims to, otherwise, adopt a life cycle approach. However, the carbon payback figure was calculated against the DECC Grid intensity estimates so this value at least should have a reduced sensitivity to these potential under estimates. This also indicates that the carbon payback figure is in line with the precautionary approach here as the displaced carbon was calculated with respect to one of the lowest National Grid estimates available. The specific carbon intensity of the Barrage is reported to be 0-23 kg.CO_2/MWh with a displaced carbon payback of -0.8-7 years (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. Table 4.).

4.8 SUMMARY

UK waters are predicted to contain more energy potential than that of almost any other country in the world. 50% of the total European tidal resource and around 35% of the total European wave resource is located in UK waters (Her Majesty's Government 2013). The highest energy potential site is found in the tidal estuary of the Severn, which has the second largest tidal range in the world. This energy represents a highly predictable and consistent renewable resource for electricity generation. It is essential that the UK exploits this resource in order to achieve a sustainable energy future. Not only does the UK have access to a substantial marine resource, it has the intellectual and industrial expertise to develop the technology required to harness it. Some significant successes have already been achieved by UK based technology systems, such as the *Pelamis* 'sea snake' and the SeaGen tidal stream turbine, and further projects are planned. However the scale down of government subsidies for technology development and the closure of some of the, so-called, 'quangos' that had previously supported such developments raises some concerns about the future of the UK marine industry. It seems that in the UK we have abundant resource and technical innovation to harness marine power but the remaining, and substantial, limitation of finance is holding development back.

Marine power technologies are split into: tidal range technologies, which exploit the head differential created in estuaries by the tide, tidal stream technologies, which typically operate like under water 'wind' turbines in the tidal current, and wave technologies, which exploit the oscillating motion of surface waves. Most technology innovation in the UK has involved tidal stream and wave technologies but there is still yet to be full scale energy plant commissioned. However, there are a handful of existing tidal barrages operating across the globe, the most local one to the UK being La Rance in northern France. Not only is the tidal barrage a proven technology, it also offers the largest generating capacity. These points, along with access to the second largest tidal range in the world makes a tidal barrage, specifically in the Severn estuary, the most important marine project for UK energy strategy.

The idea of energy generation in the Severn estuary has already had a long and convoluted history in the UK. It was first explored when Lord Brabazon formed the first Severn Barrage Committee in 1925 (Spevack, Jones and Hammond 2011). The Bondi Committee revisited the idea in the 1970s and put forward a proposal for a barrage stretching from Cardiff to Weston-Super-Mare, which marked the start of what is generally regarded as *the* Severn Barrage. The Severn Tidal Power Group put forward the most comprehensive design study so far completed in 1989 (Severn Tidal Power Group and the Department of Energy 1989) which has formed the basis of every subsequent analysis so far, including the one presented in this thesis. Most recently the idea was 'moth-balled' by the then government in 2010 but has recently been resurrected by the private consortium Corlan Hafren (Barry 2012). It seems the Severn Barrage scheme is a recurring proposal and, hence, adding to the knowledge base on this scheme is essential. All studies mentioned above have actually included words to this effect in their conclusions. Furthermore, if the UK is to meet its carbon reduction and/or renewable targets, then considerable technology change is inevitable. Decisions have to be made on which new technologies to invest in, in terms of energy and carbon investment as well as financial, and those decisions are best made comparatively. Even if a Severn Barrage is never built, robust assessments of the proposal provide benchmarks by which to judge other schemes. Further to this, tidal barrage schemes could be implemented in sites across UK, and the rest of the globe. A combination of barrage schemes could provide a solution for predictable and continuous renewable energy supply. So an understanding of the impact of one scheme is vital for estimating the impact a viability of multiple schemes. Hence, it was decided that an examination of the potential role of the Severn Barrage, in the context of a potential decarbonised electric future was required.

CHAPTER 5. LCA CASE STUDY: SEVERN BARRAGE TIDAL POWER SCHEMES

5.1 IN THIS CHAPTER

This chapter is a comprehensive report of the LCA carried out on the Severn Barrage tidal scheme. A thorough Inventory Analysis is presented which demonstrates the considerable improvements made in this assessment other previous ones completed. An extensive Results Interpretation is given, inclusive of the possible range of error generated by examining a variety of likely inventory choices identified. The study identifies areas in the Severn Barrage design are most impactful and where improvements could be made. The potential impact savings that are available from the scheme in comparison to power provided by the UK National Grid mix are estimated.

5.2 OVERVIEW OF THE SEVERN BARRAGE TIDAL POWER SCHEME

The Cardiff-Weston Barrage scheme for the Severn Estuary is an example of a marine power system which is driven by the tidal range. The Barrage would trap a large volume of water on the landward side as the tide comes in, and then as the tide goes out a head differential would be created so that water will flow through turbines mounted in the Barrage, from land to sea, under gravity alone and generate electricity. It is estimated that the Barrage would reduce the tidal range in the estuary basin by about 50%. Low tide levels would be raised up to approximately current mean sea level and high tide would lowered to 1m below current high tide. The most current design, which is yet to be officially released by the private consortium Corlan Harfren, may differ somewhat, but the design adopted for this case study is taken from that examined in the SDC study (Black & Veatch 2007) which is almost exactly that which was put forward by the STPG (Severn Tidal Power Group and Department of Energy 1989).

The scheme would be a single, renewable installation and is predicted to generate 17TWh per year, to the nearest 1TWh (Severn Tidal Power Group and the Department of Energy 1989). This would constitute 4% of the UK electricity supply and 0.6% of the total UK energy supply (Sustainable Development Commission 2007). The plant consists of a 16.1km, concrete barrage stretching from Lavernock Point near Cardiff, South Wales, to Brean Down near Weston-Super-Mare, South West England. The Barrage itself would be made up of a row concrete caissons that would be manufactured in dry casting yards, then floated in the water and towed-out by tug boats. Each caisson would then be sunk into a pre-dredged foundation across the channel and grouted into position alongside its neighbours. 216 turbines would be set in specific turbine caissons that make up the barrage structure. Embankments would be built out from the shore side at either end of the barrage. Last to be constructed would be the road across the top of the barrage (Severn Tidal Power Group and Department of Energy 1989). Figure 19 shows the layout of the proposed Severn Barrage installation.

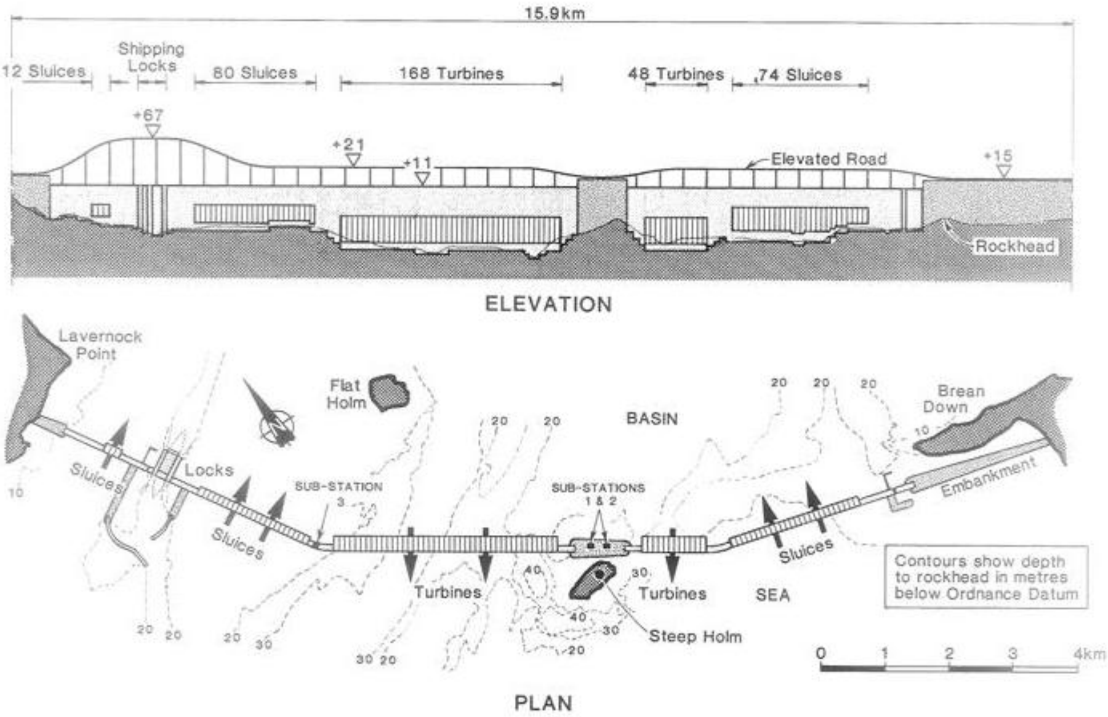

Figure 19 Layout of Severn Barrage as proposed by the STPG Report (Severn Tidal Power Group and the Department of Energy 1989)

The published studies assume that the plant will only generate when the tide is ebbing, i.e. when flow is from the basin out to sea. Generation will be most efficient when the water level difference, or head, is greatest. At high tide the water level on the sea ward side of the Barrage will be slightly higher than of the basin side. As the tide begins to ebb the sea level will drop until it equalises with the basin level. After the water levels have equalised the plant could begin to generate but, due to the very small water level differential, output will be very limited. In order to improve overall efficiency, it is proposed that for some time following water level equalisation, the turbines should be operated in reverse and pump water from the sea ward side into the basin to increase the head before generation is allowed to begin. This is referred to as 'ebb generation with 'flood pumping''. The SDC reports that the 'flood pumping' would contribute to a net gain in output of around 3% (Sustainable Development Commission 2007). The STPG (Severn Tidal Power Group and the Department of Energy 1989) reported that the adoption of 'flood pumping' could also be the most economically efficient operating mode, stating that, "... by adopting an appropriate time variant tariff structure for selling the energy from ebb generation and buying the energy for 'flood pumping', the Barrage operation could be optimised to maximise the value of the energy sent out". A water level graph presented in the STPG report, and recreated in Figure 20, suggests that pumping would occur for approximately 1 hour in every tidal cycle.

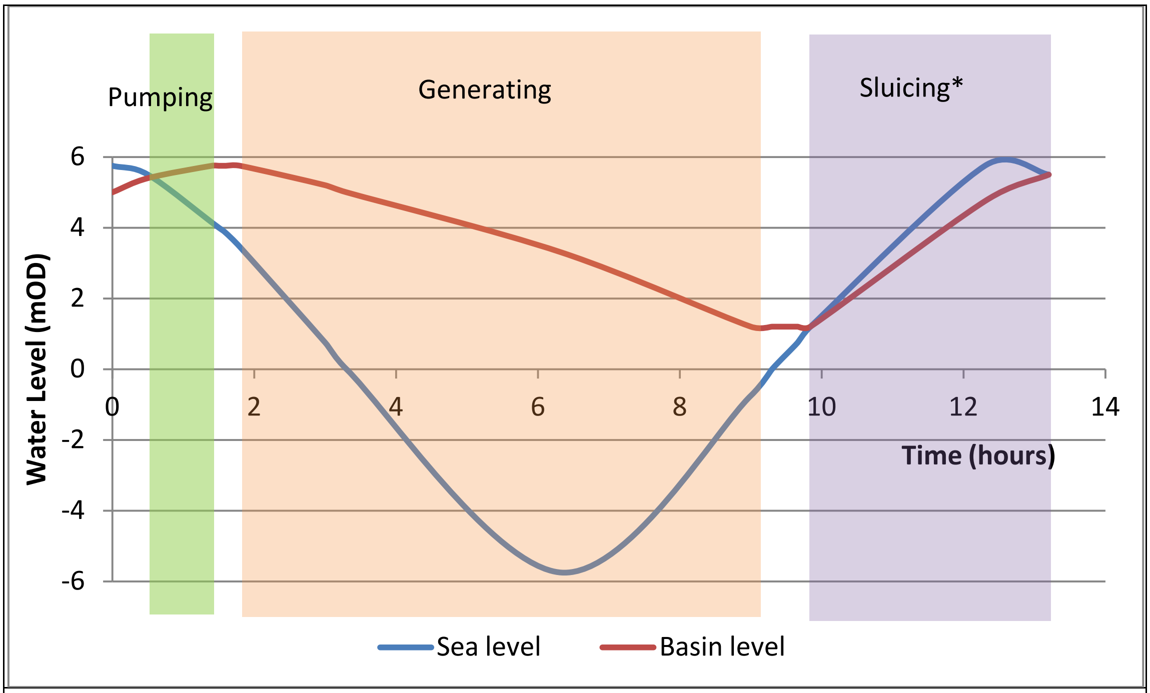

Figure 20 Tide and Basin Levels, recreated from Figure 2.10 of The Severn Barrage Project: General Report (Severn Tidal Power Group and the Department of Energy 1989)

***'Sluicing' is when the sluice gates are opened to allow the water to flow naturally from the seaward side back into the basin.**

5.3 GOAL AND SCOPE

The analyses carried out on the Severn Barrage scheme so far were considered insufficient in terms of assessing the overall lifetime environmental impact of the system and hence, to fulfil the data requirement the Transition Pathways consortium research. Also, none of the previous studies include any estimates for any environmental impacts other then energy demand and carbon emissions. The Roberts' study (Roberts 1982) was based largely on financial data which is a broad assumption and there is little evidence to suggest that this can be extended to a wider range of environmental impacts. Neither the SDC (Black & Veatch 2007) nor the Shawater (Woollcombe-Adams, Watson and Shaw 2009) studies make any detailed estimate for the operation life stages. The Spevack study (Spevack, Jones and Hammond 2011) streamlined the data available in the above literature but excludes some large areas of the life cycle because of data gaps. The DECC carbon footing printing calculation (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010) does develop a more comprehensive inventory for the operation stage but does not specify values and uses very low, "point of production" estimates for the carbon intensity of the operational power demand. Therefore, a more detailed environmental Life Cycle Assessment, LCA, of the Severn Barrage was required.

The purpose of this study is to estimate the total potential environmental burden of electricity generated by the proposed Cardiff-Weston Severn Barrage scheme and to make a comparison with the UK National Grid as it was in 1990 and 2008, and with how it potentially could be in 2050. Wherever the term 'Severn Barrage' is used in the study it refers to the Cardiff-Western scheme only. It is a streamed lined study as the life cycle inventory, LCI, is based on, and largely limited to, that which is available from existing technical and economic assessments. However the study also plugs some of the data gaps previously identified and alternative representations of the critical inventory data have been developed in order to test the robustness of the assumptions made in existing assessments.

5.3.1 SENSITIVITY: INVENTORY RANGE OF ERROR

As the Severn Barrage is still only at the proposal stage, the exact nature of the materials and processes that will be used to construct, operate and maintain the plant are still undecided. Hence multiple possible options are developed for some entries in the inventory analysis by changing the material or resource type or supplier. Through iterative impact assessment, these options were then grouped to give 3 separate inventories representing the 'initial' inventory which is most in line with the data provided by previous studies, and two extreme inventories which represent the 'best' and 'worst' case scenarios. This also enables identification of those areas that are most sensitive to change and, simultaneously, what design choices would be least impactful

5.3.2 SYSTEM BOUNDARIES

The design lifetime of the Severn Barrage is 120 years (Severn Tidal Power Group and the Department of Energy 1989) and can be described as consisting of the following 4 life cycle stages:

- Construction, consisting of: 'cradle (to gate) to site' which refers to the embodied impact of the construction materials, encompassing the extraction and processing of the raw material, the manufacture of parts and the transportation to site and; 'on site activities', specifically channel dredging, caisson casting and caisson tow out.
- Operation, consisting of the direct and ancillary processes required to operate the plant.
- Maintenance, consisting of the embodied impact of any additional materials that might be brought onto site for large scale maintenance following the Barrage commissioning.
- Decommission.

Following the review of the available data it was decided that:

- Construction be limited to those materials and activities listed in the existing literature;
- Operation be limited to the amount of electricity drawn from the Grid only;
- Maintenance be limited to the replacement of the turbines only, and that;
- Decommission is omitted from the quantitative inventory and, hence, the actual LCA results. However a qualitative discussion of disposal options and their likely relative impact is presented.

Any materials or activities that are not directly associated with the processes within the physical boundaries of the Barrage plant are excluded from the inventory. For example:

- Inland infrastructural work required to connect the plant to the National Grid. The results of this study are likely to be used to decide between innovative proposals for low carbon generation plants, all of which a likely to require infrastructural changes to the Grid, therefore this was not considered relevant to this assessment.

Figure 21 provides a visualisation of the processes that fall within the system boundaries for the study and those that do not.

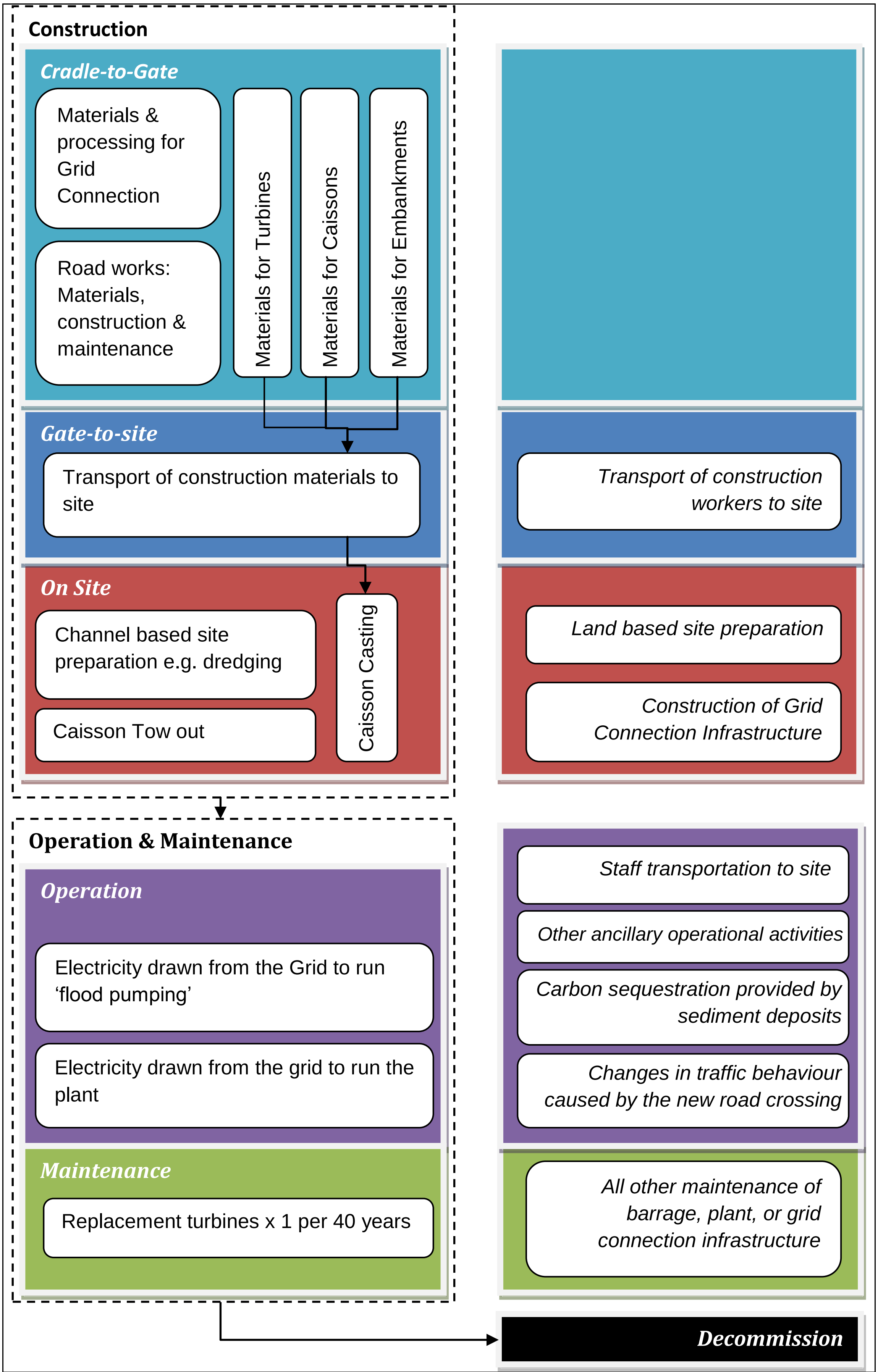

Figure 21 Flow diagram showing the system boundaries of the LCA study of the Severn Barrage

5.3.3 FUNCTIONAL UNIT

For comparing the impact of the power generated with that of the five options for the National Grid mix, the impact allocated to power generation is resolved to the specific functional unit of 'impact per unit generated', one unit being equal to 1MWh.

5.4 LIFE CYCLE INVENTORY ANALYSIS

5.4.1 CONSTRUCTION

To simplify the task of compiling the inventory for the construction stage, this has been split into the two sub-stages of:

- Construction Materials and;
- On Site Activities

5.4.1.1 Construction Materials

A summary of the material types and quantities required for each component and their journey to site where known is presented in Table 5.

Caissons: The Cardiff-Western Barrage would be made up of a total of 175 concrete caissons. A caisson is a water tight chamber with appropriate features for its specific use that make up the building blocks of the barrage. Figure 22 shows the design of a standard plain caisson and Figure 23 shows a sluice caisson, demonstrating the sort of features that could be included in a specialised caisson.

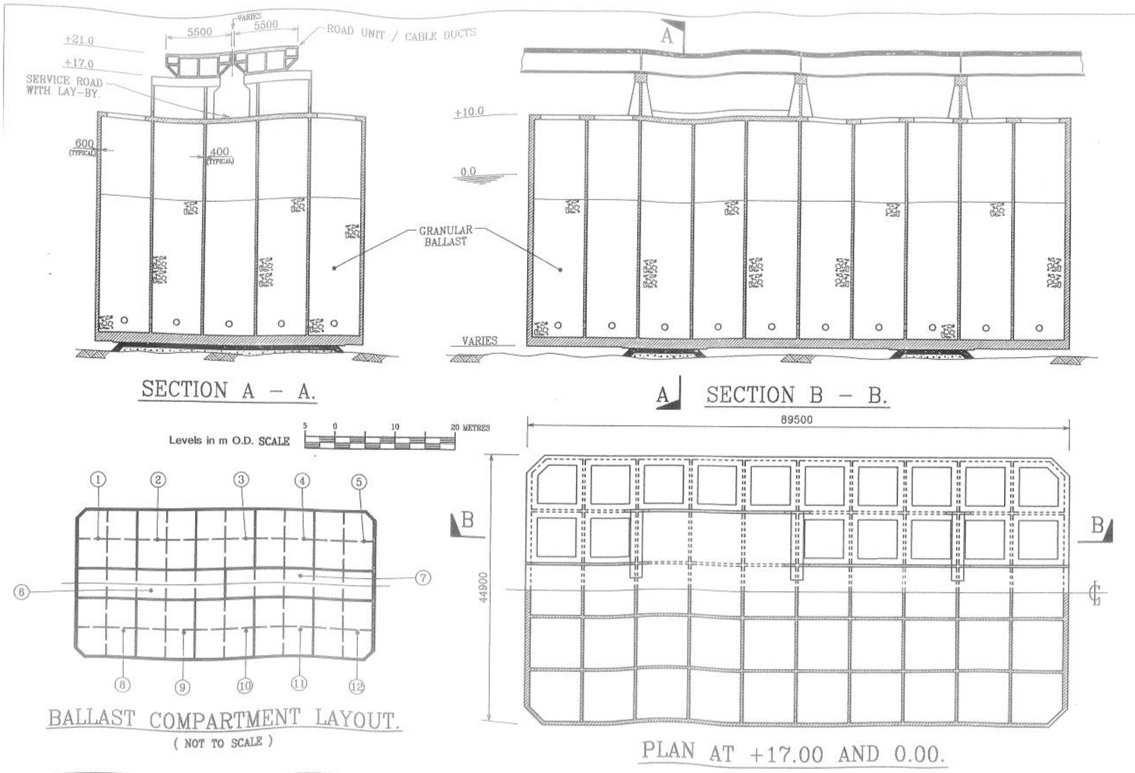

Figure 22 Engineering drawings of a plain caisson (Black & Veatch 2007, Research Report 3. Figure 4.1(6))

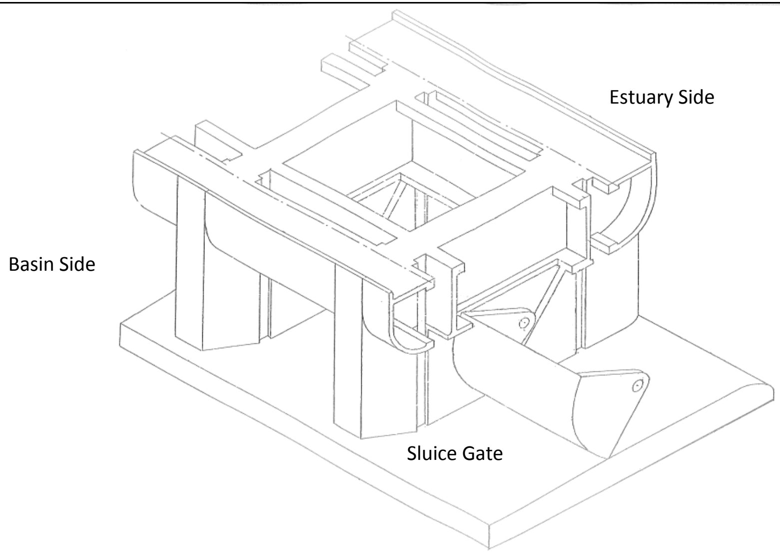

Figure 23 Isometric view of sluice caisson (Black & Veatch 2007, Research Report 3. Figure 4.1(4))

The quantity and types of different caissons in the Severn Barrage construction are;

- 54 turbine caissons,
- 46 sluice caissons,
- 24 caissons for 2 ship locks - 12 caissons each,
- 2 caissons for 1 small craft lock, and
- 47 plain caissons,

Data was taken from the ICE database (Hammond and Jones 2010) in order to provide an average representation of cement manufacture from UK suppliers. Pulverised fuel ash, PFA, is considered a zero carbon material and can be used to substitute 6%-35% of the cement required in a concrete mix (Standards Policy and Strategy Committee 2000). In line with the Spevack study, it has been assumed that a maximum of 6% of cement would be replaced with PFA. No data was readily available for PFA production in the UK or even Europe so it was necessary to extract data from the United States Life Cycle Inventory, USLCI, database (National Renewable Laboratory 2008). This is obviously a mismatch in geographical data but as the maximum PVF input will be 6% of the total cement requirement and actually has a negligible contribution to the overall impact, this is considered an allowable inconsistency. Fine aggregate is assumed to be sand and coarse aggregate to be crushed rock. It is estimated that the aggregate requirement of both types would be largely met by quarries in Wales and the West of England, which are predominately limestone and sandstone. Data for sand and limestone have been taken from the EcoInvent database (Kellenberger and Kunniger 2004). The Spevack study suggests that if the demand for coarse aggregate cannot be met by local quarries, the most likely alternative source would be the remote Glensanda Super Quarry in Scotland, which is an igneous rock quarry, largely granite (Hart-Davis 1998). However, as the EcoInvent database does not include an entry for the quarrying of granite but does for that of basalt, an adaptation of the basalt data (Althaus and Classen 2007) was used as a representation. Basalt is a considerably harder material than granite, however the differences in the processing between granite and basalt is estimated to be significantly less than the differences between granite and limestone, and this is where the comparisons are drawn in the sensitivity testing. Data was taken from the

ELCD 2.0 database (GreenDeltaTC 2010) to provide a global average representation of steel reinforcement bar.

Turbines: Four turbines will be located in each of the 54 turbine caissons, making a total of 216 turbines (Black & Veatch 2007). Each turbine is simply represented as 10% copper and 90% steel (Woollcombe-Adams, Watson and Shaw 2009), giving a total mass requirement of 43.2kt of copper and 388.8 kt of steel. Data for both copper and steel was taken from the EcoInvent database (Althaus and Classen 2007). None of the studies referred to thus far include any data or even discussion on the turbine manufacture process or its associated energy, carbon or financial costs. Due to this lack of data, this process is excluded from the inventory for this study also.

Embankments: The embankments are assumed to consist of 16.3 Mt of rock, 29.1 Mt of sand and 0.2 Mt of fabricated steel. The rock is assumed to be identical to which ever rock type is used for the coarse aggregate representation, but excluding any crushing process. It has been assumed that the full sand requirement for the embankments would be produced by the onsite channel dredging so has no additional transportation, further discussion of the channel dredging is found in 5.4.1.2 and of the embankment materials in section 5.4.2. Data for sand was taken from the EcoInvent database (Kellenberger and Kunniger 2004). Fabricated steel has been represented by data for 'reinforcing steel' taken from the EcoInvent database (Althaus and Classen 2007). Figure 24 shows a cross-sectional diagram of the showing the embankment design.

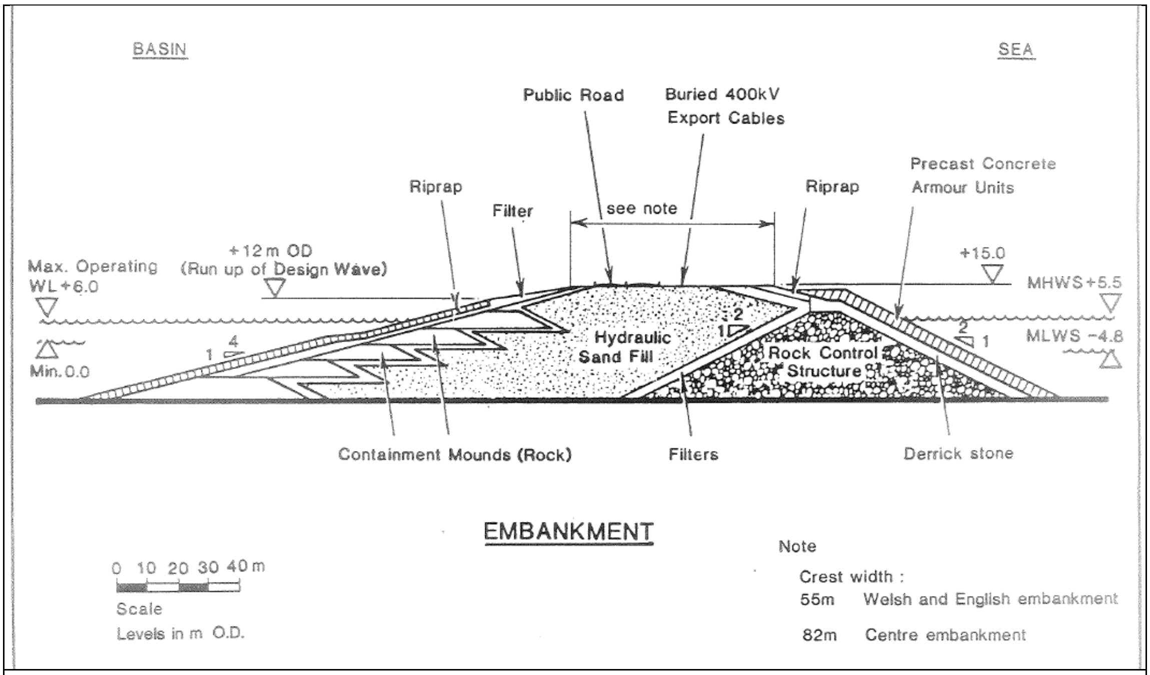

Figure 24 Cross-sectional diagram showing embankment design (Black & Veatch 2007, Research Report 3. Figure 4.1(10))

Road Works: Data for the road works was also taken from the EcoInvent database. The road work database entry includes all the necessary materials to construct and maintain the road for 120 years, plus the transportation of those materials (Spielmann 2007). The road works were represented in the LCI according to the following calculation:

$$16.1\ km\ of\ road \times 120\ years\ of\ life = 1{,}932\ kmy\ of\ road\ works$$

National Grid Connection: No site specific data for the additional infrastructure required for connection to the National Grid was available so an adaptation of data from EcoInvent was used. Inventory data for the Grid connection for 30 kW, 150 kW, 600 kW and 800 kW onshore windfarms (Burger and Bauer 2007) was used to make a scaled estimate for the material required for the Grid connection infrastructure.

Gate to Site: Estimations of the distances that each construction material type would have to be transported, from supplier to site, and the likely transportation modes used were made using the work completed by Spevack (Spevack, Jones and Hammond 2011). Data for all transportation vehicle types was extracted from the EcoInvent transport database (Spielmann 2007); ocean transportation is assumed to be via, 'transoceanic freight ship', road transport to be by 'fleet average' 16 t lorry and rail to be by 'freight rail'.

Table 5 summarizes all the data that was used to compile the inventory options to represent the material flows of the construction stage, i.e. exclusive of 'on site' activities.

Component/EcoInvent dataset	*Material*	*Quantity (tonnes)*	*Supplier Location*	*Journey*	*Transport Type*	*Distance (km)*
CAISSONS						
Average UK Portland cement(Hammond and Jones 2010)	Cement	(max) 2 900 000	Lafarge Cement UK (Aberthaw)	Aberthaw - Cardiff	Road	24
			CEMEX UK Operations (Rugby)	Rugby - Daventry	Road	18
				Daventry – Birmingham	Rail	80
				Birmingham - Wentlooge	Rail	182
				Wentlooge - Cardiff	Road	16
			Lafarge Cement UK (Cauldon)	Cauldon – Burton-on-Trent	Road	40
				Burton-on-Trent – Wentlooge	Rail	230
				Wentlooge - Cardiff	Road	16
Dummy Fly Ash (National Renewable Energy Laboratory 2008)	Pulverised Fly Ash	(max) 174 000	Lafarge Cement UK (Aberthaw)	Aberthaw - Cardiff	Road	24
Sand, at mine (Kellenberger and Kunniger 2004)	Fine Aggregate	5 000 000	South Wales	St Bridas Bay - Cardiff	Road	167
			North Wales	Conwy - Cardiff	Road	309
			West Midlands	Market Drayton – Cardiff	Road	248
Limestone, crushed, for mill (Kellenberger and Kunniger 2004)	Coarse Aggregate	9 200 000	South Wales	Pembroke or Haverford West - Cardiff	Road	156
			Re-used from channel dregs	n/a	n/a	n/a
Adapted from basalt, at mine(Althaus and Classen 2007) with 'crushing' according to limestone entry (Kellenberger and Kunniger 2004)			Glansanda	Glensanda Port - Cardiff	Ship	676
Steel rebar, blast furnace and electric arc furnace route (GreenDeltaTC 2010)	Rebar	900 000	Celsa UK	Tremorfa – Cardiff	Road	4
			Clwyd Rebar	Wrexham - Cardiff	Road	227
			Cogne Stainless Reinforcement	Rotherham - Cardiff	Road	326
TURBINES						
Copper, secondary, from electronic and electric scrap and recycling, at refinery (Althaus and Classen 2007)	Copper	43 200	Voith Hydro SL	Ibarra, Spain - Bayonne	Road	133
Chromium steel 18/8, at plant (Althaus and Classen 2007)	Steel	388 800		Bayonne - Cardiff	Ship	999
			Voith Hydro AS	Trondheim, Norway - Bristol	Ship	2 050
			Alstrom Power	Grenoble - Marsailles	Road	307
				Marsailles - Bristol	Ship	3 410
EMBANKMENTS						
Limestone, at mine (Kellenberger and Kunniger 2004)	Rock	16 300 000	South Wales	Pembroke or Haverford West – Cardiff	Road	156
Adapted from basalt, at mine(Althaus and Classen 2007)			Glensanda	Glensanda Port - Cardiff	Ship	676
Sand, at mine (Kellenberger and Kunniger 2004)	Sandfill	29 100 000	From channel bed	n/a	n/a	0
Reinforcing steel, at plant (Althaus and Classen 2007)	Fabricated Steel	200000	unknown	n/a	n/a	0
ROADWORKS						
Road/CH/I U (Spielmann 2007)	Roadworks	16.1 km	unknown	n/a	n/a	0
NATIONAL GRID CONNECTION						
Edit of 'Wind power plant 800kW, moving parts/RER/I U' (Burger and Bauer 2007) x42	Aluminium	0.0017	unknown	unknown	unknown	n/a
	Copper wire	630				
	Polyethylene	309				
	PVC	222				
	Steel bar, low-alloyed	2.65				
	Lead	0.021				
	Tin	0.021				
x2	Polypropylene	0.04				

Table 5 Life cycle inventory data for the material flows of the construction stage of the Severn Barrage, showing material requirements (Black & Veatch 2007) (Woollcombe-Adams, Watson and Shaw 2009) with predicted suppliers and estimated methods and distances for transportation gate-to-site (Spevack, Jones and Hammond 2011)

5.4.1.2 'On Site' Construction Activities

Despite the considerable investigation that has been carried out by other parties since the publication of Roberts' study (Roberts 1982), it remains the authority on assessing the resources and impacts associated with the onsite construction activities, namely channel dredging, caisson tow out and caisson casting. The study offers total energy demand estimates for each activity based on their financial cost. While this approach has its merits, it was felt that assuming a direct link between economics and environmental impact was too simplistic an approach for this study so the inventory analysis of these 'on site' activities focused on developing alternative representations based on technical rather than financial evidence.

Channel Dredging: Roberts (Roberts 1982) estimates $1.16\times10^6 m^3$ of dredged material would be removed from the channel at a cost of £24 million, at 1979 costs. An energy consumption estimate of 2,160 TJ is derived based on a conversion factor of 90MJ/£(1979). Using this data an energy conversion factor of 1826MJ/m^3 can be derived and applied to the revised SDC volume estimates. In an attempt to validate the Roberts estimate, Spevack (Spevack, Jones and Hammond 2011) derived embodied energy estimates for equivalent material volumes extracted from land based quarries, using the ICE database (Hammond and Jones 2010). Spevack concluded that the final estimates were close enough to show that they were valid, so the Roberts' estimate was used in her study. The resulting validation comparison is presented in Table 6.

	Roberts Estimate (Roberts 1982)	**Spevack Estimate** (Spevack, Jones and Hammond 2011)	
Material Type	**Energy (TJ)**	**Volume dredged** (Black & Veatch 2007) **(m^3)**	**Energy (TJ)**
Sand		10 800 000	2 000
Rock		7 200 000	29 700
Total	*33 500*		*31 700*

Table 6 Calculation of energy used in the dredging of the Cardiff-Weston Barrage site

The assumption, that energy expanded in extracting material from land would be equivalent to the extraction of the same material type from the sea bed is rather simplistic as there is no evidence to suggest that the two processes are similar and should not be used to justify the Roberts' estimate. Hence a re-estimate was calculated for this study. In 2008 the Crown Estate published figures for the kg of fuel used per tonne of material dredged for 2 long-haul dredgers, referred to as vessels A and C, and 2 short-haul dredgers, referred to as B and D (Kemp 2008). The dredgers used at the Severn Barrage construction site will be short-haul as the material dredged will probably be used on site. Table 7 shows the results for the 2 short-haul dredgers.

	Vessel B	**Vessel D**
Fuel used (kg)	142 000	83 000
Tonnage landed (tonne)	85 518	57 118
Overall fuel use (kg/t)	1.7	1.5

Table 7 Calculation of total fuel use per tonne of material for short-haul dredgers (Kemp 2008)

An estimate of the mass of material removed can by derived using a density approximation for each of the types of material. This mass value can then be used to estimate the total fuel required to dredge the channel for the Severn Barrage construction. This process is shown in Table 8.

Material Type	**Volume dredged** (Black & Veatch 2007) **(m^3)**	**Density estimate range (kg/m^3)**	**Mass dredged range(t)**	**Max fuel used, assuming vessel B (kg)**	**Min fuel used, assuming vessel D (kg)**	**Average fuel use estimate (kg)**
Sand	10 800 000	1 922 - 1 442 (SI Metric n.d.)	20 757 600 - 15 573 600	34 500 000	22 600 000	28 500 000
Rock	7 200 000	2 560 - 1 760 (Natural Stone n.d.)	18 432 000 - 12 672 000	30 600 000	18 400 000	24 500 000
Total				***65 100 000***	***41 000 000***	***53 000 000***

Table 8 Calculation of fuel used in the dredging of the Cardiff-Weston Barrage site

This fuel mass estimate was then represented in the life cycle inventory using data for average European diesel (Pre Consultants 2001). For comparison, the energy demand re-estimate for the channel dredging is 2,700 TJ, in a range of 3,310 – 2,080 TJ, using the Cumulative Energy Demand impact assessment methodology (Frischknecht and Jungbluth 2003) and excluding energy from natural, 'non-capital', resources. These estimates are considerably less than the energy estimates calculated by Roberts and adopted by Spevack. This indicates that dredging at sea uses less energy than it would to extract the same volume of material from land based quarries but it is just as expensive. This seems to follow, as typically sea based transport vehicles are less energy intensive per tonne than land based transport vehicles, so it seems reasonable that the same would be true of material extraction vehicles.

It was important that an estimation of the overall ocean floor that will be 'transformed' as a result of the Severn Barrage construction was included and allocating it to the dredging activity is the most logical approach. In order to generate a range, the following method was applied. The length of the required dredging area was assumed to be equal to the barrage length, i.e. 16.1km, and the width was estimated at 150m, giving a total area of 2.42 m^2. The average estimated mass for the dredged material was used to give a transformation rate of $0.12m^2/t$ of material. This transformation rate was then applied to the average and extreme mass estimates to generate an 'initial', 'best' and 'worst' case total ocean bed transformation. The impact on land transformation in the normalized context is one of the most controversial in the ReCiPe methodology as it is generally thought that impact calculation is the least well developed and, perhaps more importantly, one of the most subjective. However, as the main part of the analysis for this study is comparative, it was decided that consistency in the impacts included was the priority.

Dredging the Severn Estuary will have significantly more environmental impacts than that that can be estimated using the fuel efficiency of the vessel. There will be an impact on the water quality and the ecology of the area caused by the disruption of the channel bed, but these types of localised impact are best assessed by an Environmental Impact Assessment, EIA, which is outside the scope of this research.

The STPG report also describes a 'drill and blast' pre-treatment regime which will remove material from the river bed before the channel dredge begins. It has proved very difficult to obtain any detail on this process or a method to represent it in the case study inventory. It is estimated, however, that the resource consumption and polluting emissions of this process would be small compared to that of the dredging itself. The main additional impacts of the 'drill and blast' process will predominantly be visual and aural which would also fall within the scope of an EIA rather than an LCA.

$Caisson\ Tow\ Out$: The Roberts study (Roberts 1982) provides a tow out energy conversion factor of 54 TJ/caisson. The revised design includes 175 caissons, as listed above, so the total tow out energy can be estimated using the following calculation:

$$54 \times 175\ caissons = \ 9\ 450\ TJ$$

An alternative inventory option was generated using the following information. The average towing distance from potential casting yards to the Barrage site is reported to be approximately 100km (Spevack, Jones and Hammond 2011). Comparison with the towing routes presented in the STPG report (Severn Tidal Power Group and the Department of Energy 1989) confirms this to be a rough but reasonable estimate. The weight of each caisson is 126 000 t (Severn Tidal Power Group and the Department of Energy 1989) and there are known to be 175 caissons required which gives a total mass to be towed of 22 050 000 t. Using these two pieces information, the tow out can be represented in the inventory using an appropriate vessel type. Limited data is available on the exact nature of the vessels that might be used for the tow out activity, the SDC report states that, "...each caisson would be towed to the site by large tugs..." (Black & Veatch 2007). Explicit data was not available for satisfactory representation of a 'large tug' so data for a 'tanker' was extracted from the EcoInvent transport database (Spielmann 2007) in order to represent a small, ocean-going vessel. For comparison, the energy demand re-estimate for the caisson tow out is 197 TJ, using the Cumulative Energy Demand impact assessment methodology (Frischknecht and Jungbluth 2003) and excluding energy from natural, 'non-capital' resources. This estimate is also considerably less than the energy estimate calculated by Roberts. This complies with the explanation for the difference in the dredging estimate, i.e. that sea based transportation is less energy intensive but more expensive than alternative transportation methods, e.g. a land based bench mark.

$Caisson\ Casting$: Table 9 shows data extracted from the Roberts study regarding the caisson casting.

Caisson Type	**No. Of Caissons**	**No. Of Casting Facilities**	**Cost (1979 £)**	**Energy Factor (MJ/1979 £)**	**Product (TJ)**
Turbine	70	2	89 000 000	50	4 450
Sluice	53	1	35 000 000	50	1 750
Total					*6 200*

Table 9 Data for determination of caisson casting energy requirements (Roberts 1982)

Roberts (Roberts 1982) also assumes that 24 'jointing' caissons will be manufactured. This allows for a total of only 147 caissons. The SDC (Black & Veatch 2007) study assumes that there would be 175 caissons as in the STPG proposal (Severn Tidal Power Group and Department of Energy 1989), and as listed in Section 5.4.1.1. The SDC estimate the cost of these 175 caissons would be £559,000,000. As there is a mismatch in even the number of caissons between the Roberts and more recent studies, a re-estimate was felt even more appropriate. According to the ICE database (Hammond and Jones 2010), an additional energy figure of 0.51 MJ/kg should be added to any estimate for a concrete structure that is precast. This value can be used to recalculate an estimate for the energy consumed in the caisson casting:

$$22\ 050\ 000\ \textit{t of caisson} \times 0.51\ \textit{MJ/kg of concrete cast} = 11\ 250\ \textit{TJ}$$

This energy estimate using the ICE data is considerably larger than the Roberts' estimate. A higher estimate was expected due to the higher number, and hence higher mass of concrete, included in the estimate. However the higher estimate could also reflect that the process of concrete casting is a relatively cheap process compared to the energy intensity and hence a financially based method would underestimate the energy demand. This energy re-estimate was represented as diesel fuel (Pre Consultants 2001) in the life cycle inventory in order to calculate the wider suite of associated environmental impacts.

5.4.2 CONSTRUCTION: RANGE OF ERROR

As discussed above and can be seen in Table 5, some of the inventory entries for the construction stage of the Severn Barrage have multiple options. For the construction materials the cement, aggregate, rock, steel reinforcement bar and turbine representations can vary in terms of the assumed distance and transportation methods gate-to-site. The cement can also vary with respect to its PFA content and the aggregate/rock can be assumed to be either limestone or granite. For the on-site activities, the amount of fuel used to dredge the channel has been shown to range depending on what the assumed density of the material dredged. The range of representations for the channel dredging is already explained in Section 5.4.1.2.

Caisson Cement: The options are as follows: pulverised fly ash[3] from Aberthaw (that would make up a maximum of 6% of the cement input), Lafarge Cement from the Cauldon plant, Lafarge Cement from the Aberthaw plant or CEMEX from the Rugby plant. In all cases bar the pulverised fly ash, the material properties of the cement, and hence the 'cradle-to-gate' impacts, are identical and the only way in which the compared products differ is in the distance and method of transportation 'gate-to-site'. A table of the characterised impact results, per one tonne of material, is presented in Table 10. Figure 25 shows the normalized impact score for each cement option in each impact category. Figure 26 shows the same information as Figure 25 but with the axes reversed in order to allow the total normalized impact score for each option to be more easily compared. As might be expected, the total impact score of the pulverised fly ash is shown to be negligible compared to the three Portland cement options. The Lafarge cement from Aberthaw has the lowest total score of the three Portland cements, so the 'best' cement option is 6% pulverised fly

[3] '*Pulverised Fly Ash*' or '*Fuel Ash*' is a by-product resulting from the burning of pulverised coal in coal fired power stations. It can substitute some proportion of the Portland cement required but it is never used in isolation (The Concrete Society 2002)

ash and 94% Lafarge cement from Aberthaw. The 'worst' is Lafarge cement from Cauldon. As the only variation between the options is that of the distance travelled to site, the variation in environmental impact is small. The Lafarge cement from Cauldon is the 'worst' or most impactful simply because it has the furthest to travel. For comparison, the impact results of 1t of average UK Portland cement is included in the results presented. The assessment shows that the impact contribution from the cradle-to-gate stage, i.e. of the material itself, far outstrips that of the gate-to-site stage, hence the most effective way to reduce the environmental impact of the cement component of the Barrage would appear to be to reduce the amount of cement required, either by using a larger percentage of PFA or by changing the caisson design.

Impact category	Unit	CEMEX Cement - Rugby	Lafarge Cement - Aberthaw	Lafarge Cement - Cauldon	Pulverised Fly Ash - Aberthaw	Portland cement, average UK
Climate change	kg.CO_2eq	864.1	860.6	868.1	0.0	857.3
Ozone depletion	kg.CFC-11-eq	0.0	0.0	0.0	0.0	0.0
Human toxicity	kg.1,4-DB-eq	54.6	53.3	55.5	0.0	52.9
Photochemical oxidant formation	kg.NMVOC	1.5	1.5	1.6	0.0	1.5
Particulate matter formation	kg.PM10-eq	0.5	0.5	0.6	0.0	0.5
Ionising radiation	kg.U235-eq	93.1	86.6	96.0	0.0	86.3
Terrestrial acidification	kg.SO_2-eq	1.3	1.3	1.3	0.0	1.2
Freshwater eutrophication	kg.P-eq	0.0	0.0	0.0	0.0	0.0
Marine eutrophication	kg.N-eq	0.5	0.5	0.5	0.0	0.5
Terrestrial ecotoxicity	kg.1,4-DB-eq	0.0	0.0	0.0	0.0	0.0
Freshwater ecotoxicity	kg.1,4-DB-eq	0.7	0.7	0.7	0.0	0.7
Marine ecotoxicity	kg.1,4-DB-eq	0.7	0.7	0.8	0.0	0.7
Agricultural land occupation	m^2	4.4	4.3	4.4	0.0	4.3
Urban land occupation	m^2	1.8	1.4	1.9	0.0	1.4
Natural land transformation	m^2	0.0	0.0	0.0	0.0	0.0
Water depletion	m^3	2.8	2.8	2.9	0.0	2.8
Metal depletion	kg.Fe-eq	7.2	6.3	7.7	0.0	6.1
Fossil depletion	kg.oil-eq	75.1	73.9	76.5	0.0	72.7

Table 10 Comparison of the characterised results by impact category of the caisson cement options (per 1t) for the construction stage of the Severn Barrage LCA case study, using Midpoint (H European) Analysis (to the 1 decimal place)

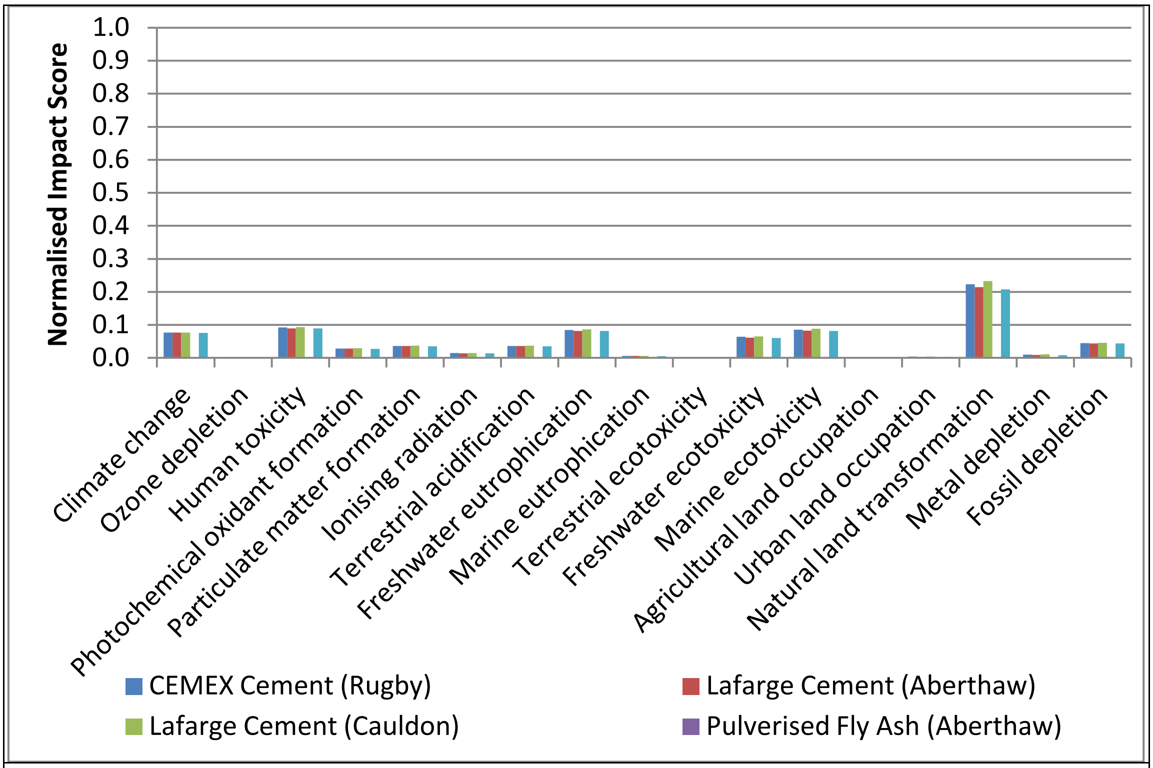

Figure 25 Comparison of the normalised results by impact category for each of the caisson cement options using Midpoint (H European) Analysis

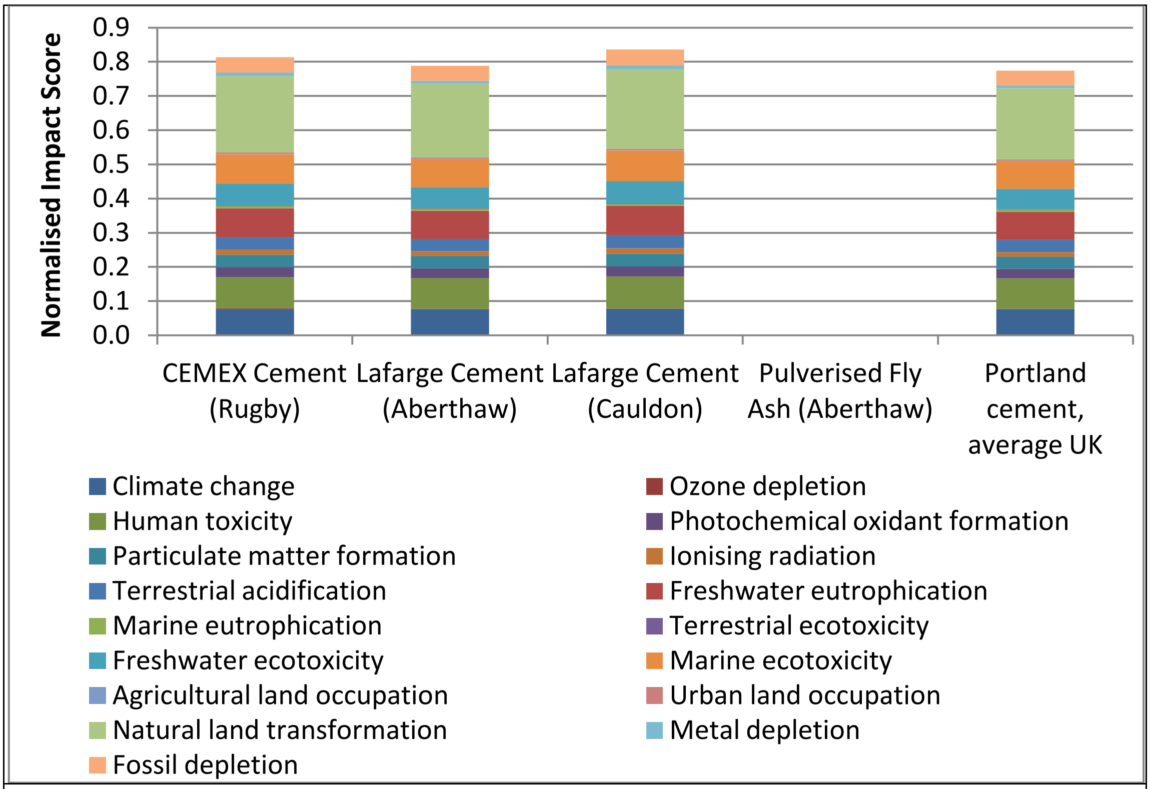

Figure 26 Comparison of the total normalised impact score for each of the caisson cement options, using Midpoint (H European) Analysis

Fine aggregate: The options for fine aggregate are all represented by sand either from St Bridas Bay in South Wales, Conwy in North Wales, Market Drayton in the West Midlands or recovered from the channel dredging. As in the case of the caisson cement, the only element that varies between these options is the distance and transport method used 'gate-to-site'. The representation of the sand recovered from the channel is still represented using the EcoInvent entry 'sand, at mill'(Kellenberger and Kunniger 2004) in order to account for the processes that would be required on site to make the material recovered from the channel suitable fine to be used as sand in concrete manufacture.

A table of the characterised impact results, per one tonne of material, is presented in Table 11. Figure 27 shows the normalized impact score for each fine aggregate option in each impact category. Figure 28 shows the same information as Figure 27 but with the axis reversed so that the options can be directly compared. As might be expected, the 'best' option is that which travels the least, that is sand recovered on site, and the 'worst' is that which travels furthest, that of sand from North Wales. What is, perhaps, more surprising is the magnitude of difference between them. The assessment shows that the sand itself has a minimal impact compared to that of its transportation. Hence, in order to reduce the environmental impact of this component, finding the most local suppliers should be prioritised over reducing material demand.

Impact category	Unit	Sand (North Wales)	Sand (South Wales)	Sand (West Midlands)	Sand only (from channel)
Climate change	kg.CO_2eq	43.5	24.6	35.4	0.0
Ozone depletion	kg.CFC-11-eq	0.0	0.0	0.0	0.0
Human toxicity	kg.1,4-DB-eq	6.0	3.6	5.0	0.0
Photochemical oxidant formation	kg.NMVOC	0.4	0.2	0.3	0.0
Particulate matter formation	kg.PM10-eq	0.1	0.1	0.1	0.0
Ionising radiation	kg.U235-eq	5.8	4.1	5.1	0.0
Terrestrial acidification	kg.SO_2-eq	0.3	0.1	0.2	0.0
Freshwater eutrophication	kg.P-eq	0.0	0.0	0.0	0.0
Marine eutrophication	kg.N-eq	0.1	0.1	0.1	0.0
Terrestrial ecotoxicity	kg.1,4-DB-eq	0.0	0.0	0.0	0.0
Freshwater ecotoxicity	kg.1,4-DB-eq	0.1	0.1	0.1	0.0
Marine ecotoxicity	kg.1,4-DB-eq	0.1	0.1	0.1	0.0
Agricultural land occupation	m^2	0.2	0.1	0.2	0.0
Urban land occupation	m^2	0.9	0.7	0.8	0.0
Natural land transformation	m^2	0.0	0.0	0.0	0.0
Water depletion	m^3	1.6	1.5	1.5	0.0
Metal depletion	kg.Fe-eq	2.6	1.6	2.2	0.0
Fossil depletion	kg.oil-eq	16.3	9.2	13.3	0.0

Table 11 Comparison of the characterised results by impact category of the fine aggregate options (per 1t) for the construction stage of the Severn Barrage LCA case study, using Midpoint (H European) Analysis (to 1 decimal place)

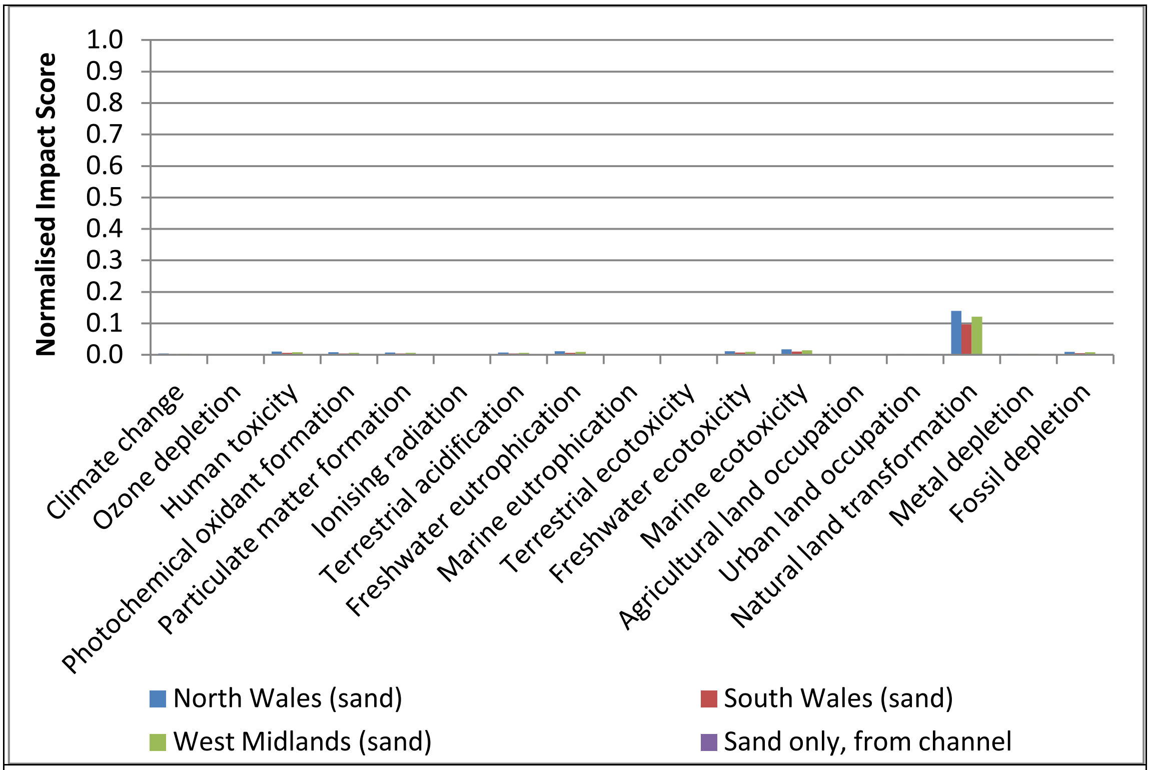

Figure 27 Comparison of the normalised results by impact category for each of the fine aggregate options using Midpoint (H European) Analysis

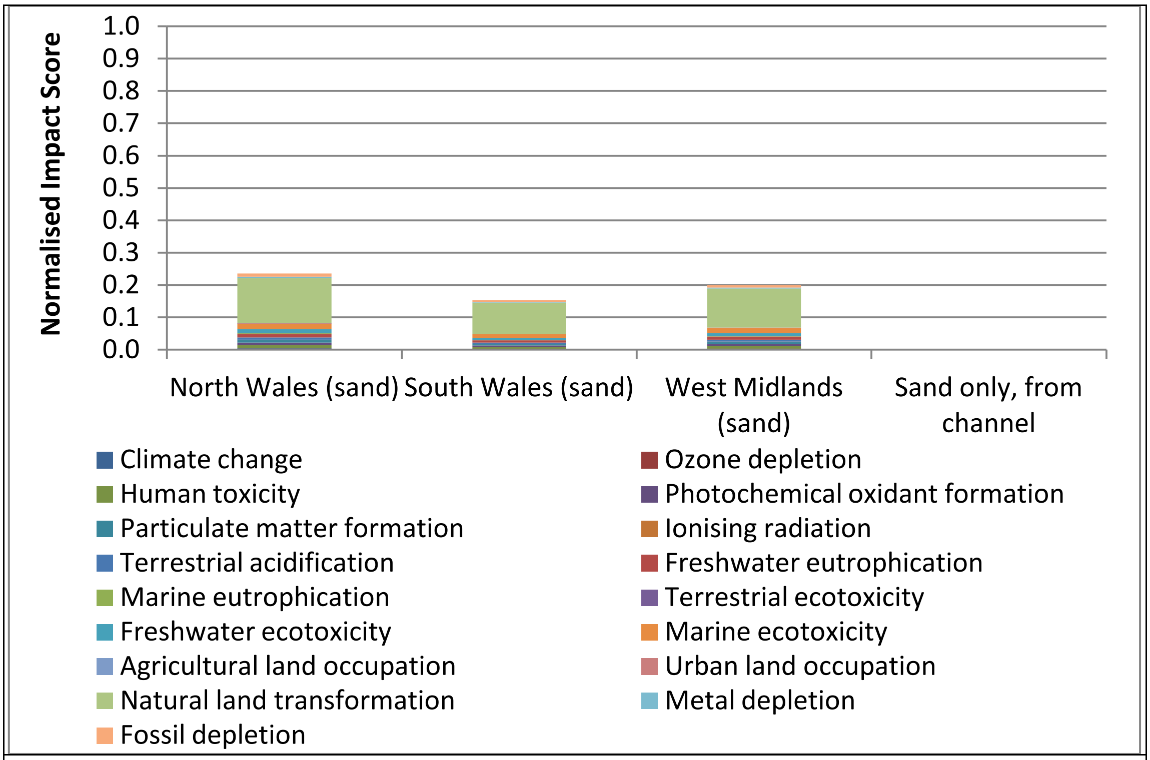

Figure 28 Comparison of the total normalised impact score for each of the fine aggregate options, using Midpoint (H European) Analysis

Coarse aggregate and rock: The options for the rock component for the embankment construction are as follows: 'locally' quarried limestone or igneous, granite, rock from Glensanda, Scotland. A table of the characterised impact results for one tonne of material is presented in Table 12, the 'local' limestone is shown to be the most impactful in four categories and the Glensanda granite is the most impactful in five. The 'local' limestone is shown to be the most impactful in the important category of climate change, and has around 54% greater GWP. However, when the values are compared with the impact of the rock only, it is clear that the impact contribution is from the transportation rather than the material. This is because it is assumed that the rock for Glensanda is carried the full distance to site by ship which typically has lower carbon emissions per unit mass per mile. In three of the categories where the Glensanda rock is estimated to be the 'worst', that of particulate matter formation, urban land occupation and natural land transformation, it is shown to be more than 95% worse, whereas the 'local limestone' is only more than 75% worse in one category, that of metal depletion.

The local limestone has such a low impact in the category of urban land occupation in comparison to the Glensanda rock, because the inventory entry for limestone assumes that the quarry will be recultivated, whereas this assumption is not adopted for the Glensanda rock entry. In the specific case of the Glensanda Super Quarry, no plans have been found for recultivation. The high score of the Glensanda rock in the category of particulate matter formation can be attributed to the fact that twice as much fossil fuel derived energy is estimated to be consumed in the building of the machines used to extract granite as those used to extract limestone. This is a reasonable assumption as it would surely take more machinery and machine power to extract a hard rock than a soft one. Furthermore, as both inventory entries are based on information from the EcoInvent (EMPA 2007) database it can be assumed that the differences between them are based on acceptable evidence.

The comparisons of the normalized results provided in Figure 29 and Figure 30 also shows that the 'best' is limestone from local sources. The greatest difference is shown in the category of natural land transformation, which is the most controversial of the categories those included in the ReCiPe suite of impacts, in the normalized context. So this result does suggest that further work would be required, independently from the ReCiPe methodology, to fully confirm which of the two options is the 'best'. However, for the purposes of this study, granite from Glensanda is the 'worst' option and 'local' limestone is the 'best'. Local limestone is already the preferred construction material because of logistic and cost benefits, and, hence, will be used in the 'initial' inventory of the Severn Barrage. Glensanda rock was proposed as an option by Spevack (Spevack, Jones and Hammond 2011) only in the instance that local quarries could not meet the construction demand. It can now be seen that the environmental assessment supports this design approach.

Impact category	Unit	Limestone - South Wales	Granite - Glensanda, Scotland	Limestone only - at mine	Granite only - at mine (adapted from Basalt entry)
Climate change	kg.CO_2eq	22.7	14.7	1.9	7.4
Ozone depletion	kg.CFC-11-eq	0.0	0.0	0.0	0.0
Human toxicity	kg.1,4-DB-eq	2.8	3.5	0.2	2.5
Photochemical oxidant formation	kg.NMVOC	0.3	0.2	0.1	0.1
Particulate matter formation	kg.PM10-eq	0.1	8.1	0.1	8.0
Ionising radiation	kg.U235-eq	2.0	3.7	0.1	2.8
Terrestrial acidification	kg.SO_2-eq	0.2	0.2	0.0	0.1
Freshwater eutrophication	kg.P-eq	0.0	0.0	0.0	0.0
Marine eutrophication	kg.N-eq	0.1	0.1	0.0	0.0
Terrestrial ecotoxicity	kg.1,4-DB-eq	0.0	0.0	0.0	0.0
Freshwater ecotoxicity	kg.1,4-DB-eq	0.1	0.1	0.0	0.1
Marine ecotoxicity	kg.1,4-DB-eq	0.1	0.1	0.0	0.1
Agricultural land occupation	m^2	0.1	0.1	0.0	0.1
Urban land occupation	m^2	0.3	8.0	0.1	8.0
Natural land transformation	m^2	0.0	0.5	0.0	0.5
Water depletion	m^3	0.1	0.1	0.0	0.0
Metal depletion	kg.Fe-eq	1.2	0.3	0.1	0.2
Fossil depletion	kg.oil-eq	8.5	4.9	0.6	2.4

Table 12 Comparison of the characterised results by impact category of the coarse aggregate/rock options (per 1t) for the construction stage of the Severn Barrage LCA case study, using Midpoint (H European) Analysis (to 1 decimal place)

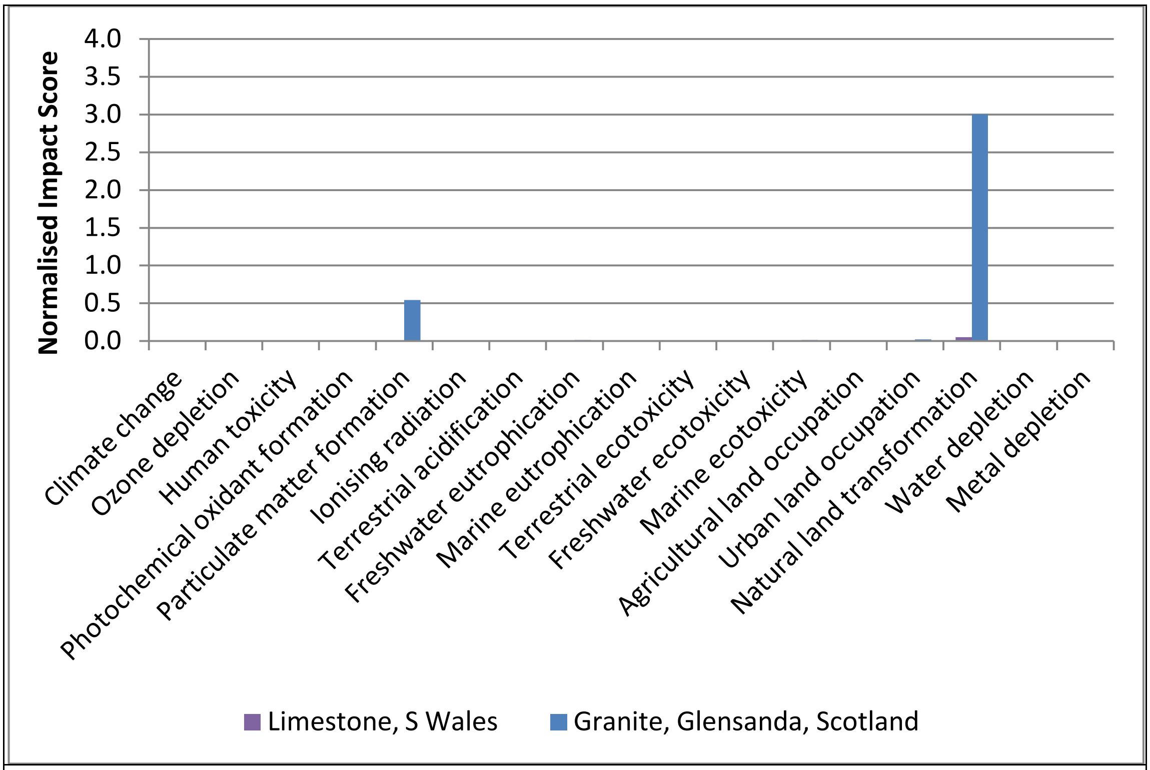

Figure 29 Comparison of the normalised results by impact category for each of the coarse aggregate/rock options using Midpoint (H European) Analysis

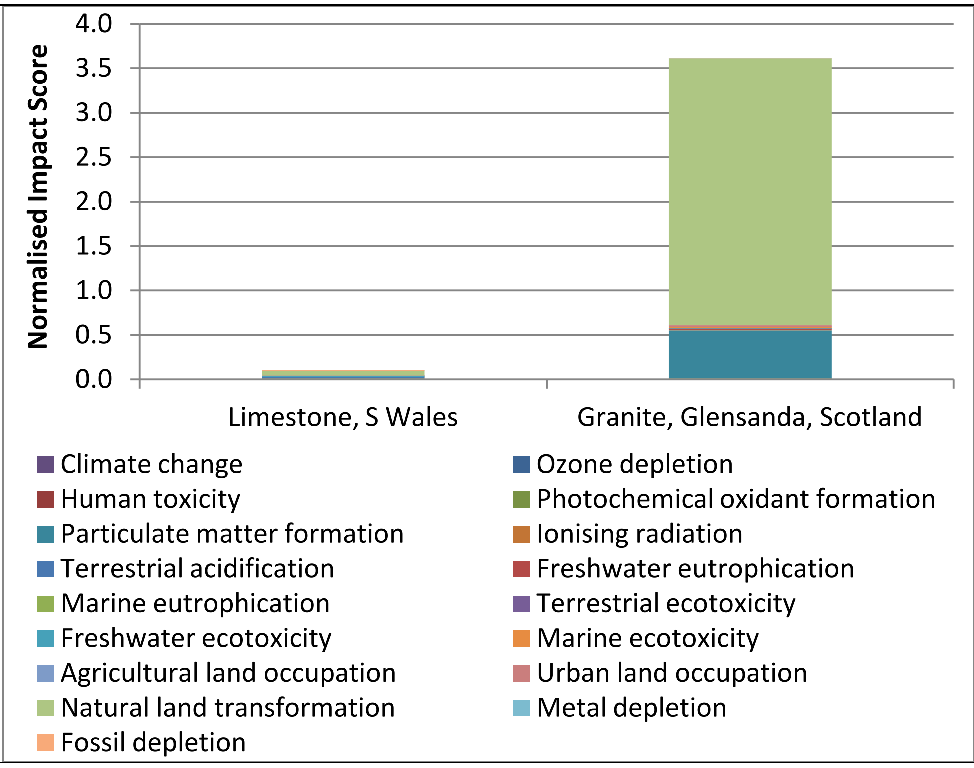

Figure 30 Comparison of the total normalised impact score for each of the coarse aggregate/rock options, using Midpoint (H European) Analysis

These two options for the rock component of the embankments, along with material recovered from the channel dredging, which is assumed to be limestone also, are the three options for the coarse aggregate component of the caisson concrete. Figure 31 compares the total normalized impact scores for the two rock options and that of the limestone only, but this figure shows the relative impact contribution from the rock itself, the transport to site and from the additional 'crushing' process which is included to represent the additional processing that would be required to turn 'rock' into an appropriate material for concrete aggregate. The amount of 'crushing' required is assumed to be identical for both types of rock and hence the impact contribution is identical for each option. It can be seen that the large overall score of the granite from Glensanda is dominated by the rock itself, this is because of the large scores in the categories of natural land transformation and agricultural land occupation which are almost entirely due to the assumptions made with respect to the mining strategy. The overall score for the 'local' limestone, which is already small relative to the granite, is dominated by the impact of the transportation. The 'crushing' dominates the almost negligible score of the limestone recovered from the channel. As was the case for the fine aggregate, the 'best' option for the coarse aggregate would be limestone recovered from the channel itself.

There is, of course, some land transformation associated with the extraction of the limestone from the channel but the material is a really a by-product of the channel dredging, to which the impact is already allocated, see Section 5.4.1.2. The allocation of the land transformation to material recovered would lead to the perverse recommendation that the material should be discarded in order to reduce the impact.

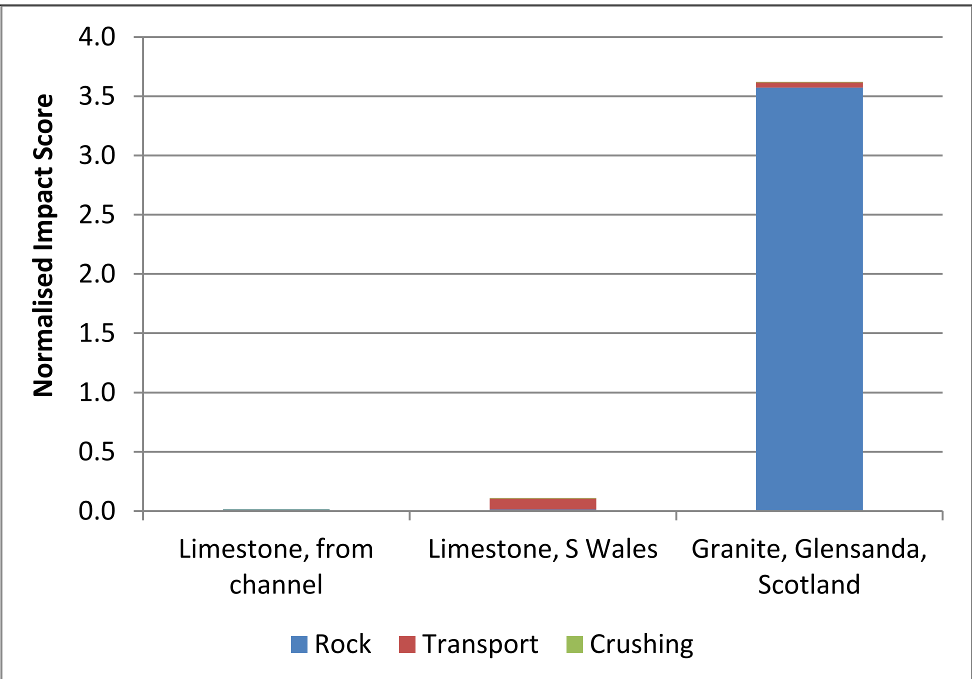

Figure 31 Comparison of the total normalised impact score for each of the coarse aggregate/rock options, using Midpoint (H European) Analysis

Caisson reinforcement bar: As with the cement and the fine aggregate, the only variation in reinforcement bar options is the supplier, and hence the distance and method used to travel gate-to-site. The three supplier options are Celsa UK in Tremorfa, Clwyd Rebar in Wrexham and Cogne Stainless Reinforcement in Rotherham. Table 13 shows the characterised results for the three options and for steel reinforcement bar only per tonne of material. Figure 32 and Figure 33 shows the normalized per category and per option respectively. These results demonstrate, again, that the most local material is the 'best' and the 'worst' is that which has to travel furthest. The Clwyd rebar is assumed for the 'initial' case. The results also demonstrate that, as is the case of the caisson cement, it is the impact of the material itself which makes the largest contribution. Hence, in the case of the steel reinforcement bar, reducing material demand or using a lower impact alternative would have the greatest effect on overall environmental impact.

Impact category	**Unit**	**Celsa UK**	**Clwyd Rebar**	**Cogne Stainless Reinforment**	**Steel rebar only**
Climate change	kg.CO_2eq	1029.0	1058.7	1071.9	1028.5
Ozone depletion	kg.CFC-11-eq	0.0	0.0	0.0	0.0
Human toxicity	kg.1,4-DB-eq	101.6	105.4	107.1	101.6
Photochemical oxidant formation	kg.NMVOC	2.1	2.4	2.5	2.1
Particulate matter formation	kg.PM10-eq	1.4	1.5	1.5	1.4
Ionising radiation	kg.U235-eq	0.0	2.8	4.0	0.0
Terrestrial acidification	kg.SO_2-eq	2.8	3.0	3.0	2.8
Freshwater eutrophication	kg.P-eq	0.0	0.0	0.0	0.0
Marine eutrophication	kg.N-eq	0.1	0.1	0.1	0.1
Terrestrial ecotoxicity	kg.1,4-DB-eq	0.1	0.1	0.1	0.1
Freshwater ecotoxicity	kg.1,4-DB-eq	0.0	0.1	0.1	0.0
Marine ecotoxicity	kg.1,4-DB-eq	0.4	0.5	0.6	0.4
Agricultural land occupation	m^2	0.0	0.1	0.2	0.0
Urban land occupation	m^2	0.0	0.3	0.5	0.0
Natural land transformation	m^2	0.0	0.0	0.0	0.0
Water depletion	m^3	3.8	3.9	4.0	3.8
Metal depletion	kg.Fe-eq	313.5	315.0	315.7	313.4
Fossil depletion	kg.oil-eq	253.2	264.4	269.4	253.0

Table 13 Comparison of the characterised results by impact category of the turbine options (per 1t) for the construction stage of the Severn Barrage LCA case study, using Midpoint (H European) Analysis (to 1 decimal place)

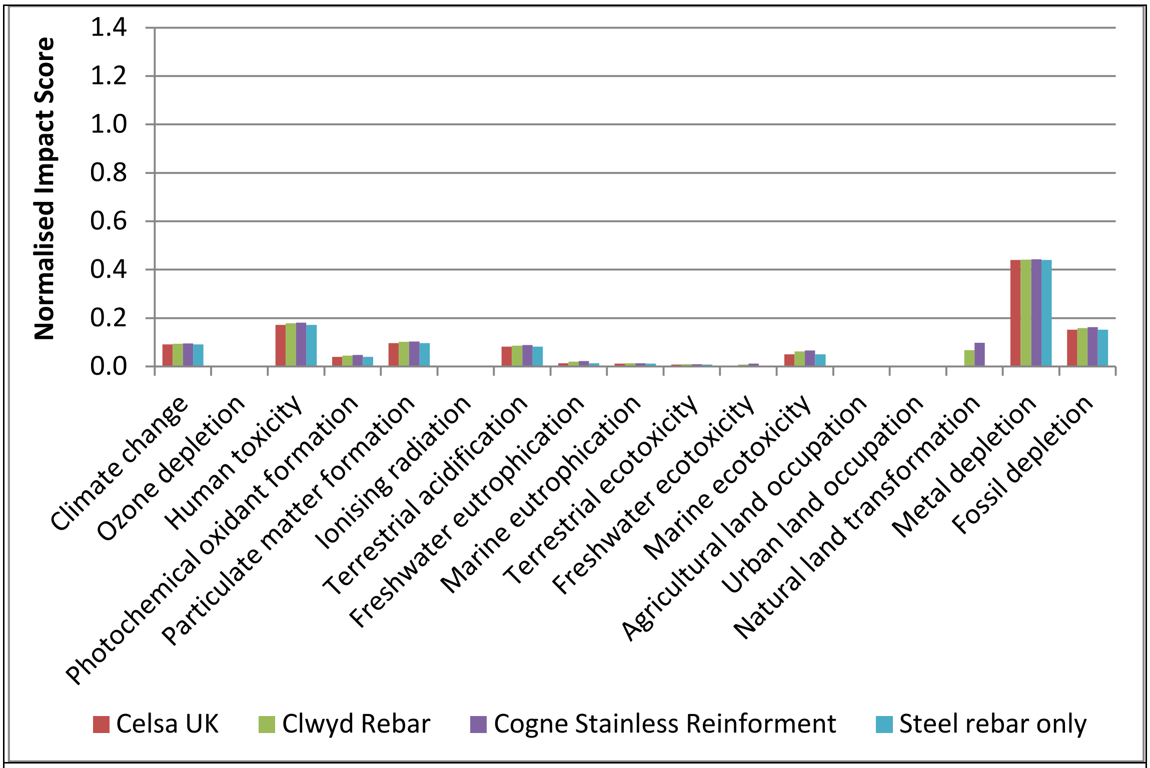

Figure 32 Comparison of the normalised results by impact category for each of the steel rebar options using Midpoint (H European) Analysis

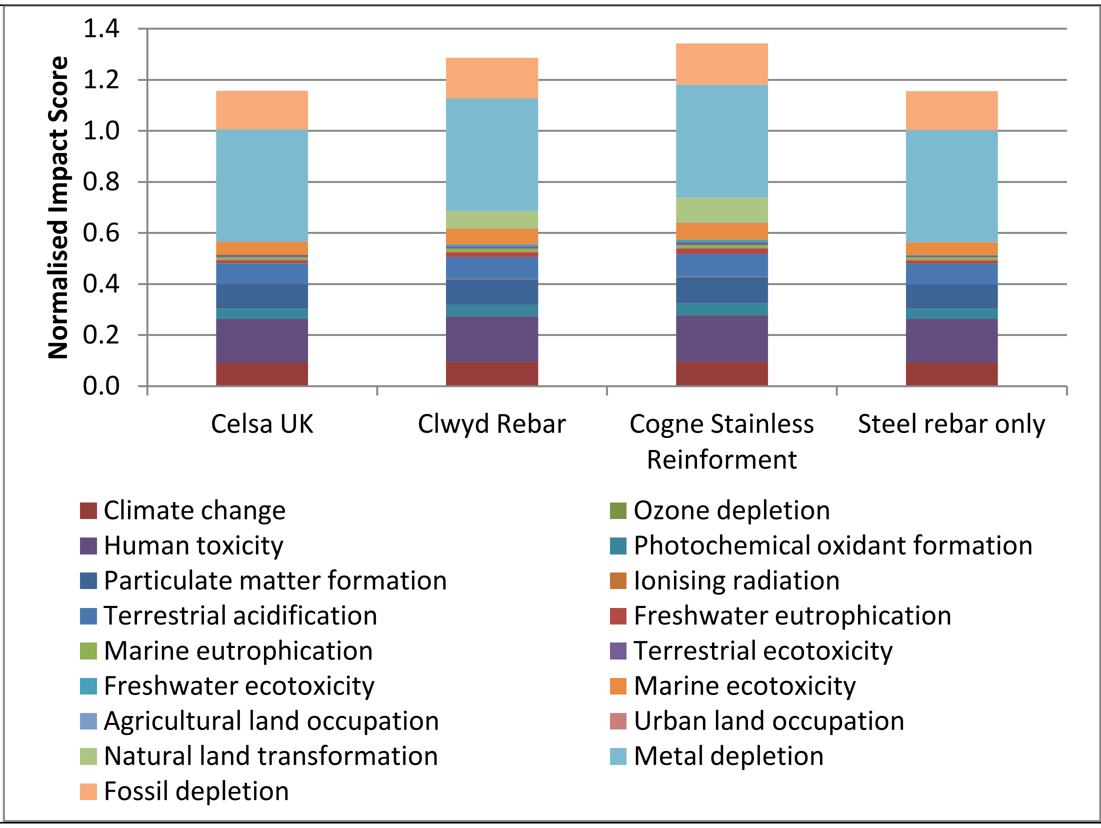

Figure 33 Comparison of the total normalised impact score for each of the steel rebar options, using Midpoint (H European) Analysis

Turbine: Once again, the only variation in option for this component is also the supplier location, and hence distance and method used to travel to site. The turbine options are a Voith Hydro SL from Ibarra, Spain, a Voith Hydro AS from Trondheim, Norway or an Alstrom Power turbine from Grenoble, France. Table 14 presents the characterised results for the three options along with results for the turbine representation only per tonne of turbine. Figure 34 and Figure 35 show the normalised results. As is the case for all components so far the 'best' option is that which travels least, i.e. the Voith Hydro SL from Ibarra, and the 'worst' is that which travels furthest, i.e. the Alstrom Power turbine from Grenoble which is delivered to site via a shipping route that travels around the full coast of Spain. The middle option, of the Voith Hydro turbine from Trondheim, is used for the 'initial' case. Despite the very long travelling distances, however, the impact is still extremely dominated by the materials used to make up the turbine, predominately the virgin steel, so the contribution from the transport is relatively very small so there is little variation between the options at all. It is unlikely that the turbine design will have much scope to reduce its material demand but perhaps an increased proportion of recycled steel could be used to reduce the overall impact. Inventory data for recycled steel has not been collected but for comparison. The existing database entry for recycled copper (Althaus and Classen 2007) suggest a 95-100% improvement on primary copper across the impact categories which gives an indication of the magnitude of the impact savings that could be made by using recycled metals where possible.

Impact category	Unit	Alstrom Power	Voith Hydro AS	Voith Hydro SL	Turbine Only
Climate change	kg.CO_2eq	4142.9	4084.2	4092.0	4062.2
Ozone depletion	kg.CFC-11-eq	0.0	0.0	0.0	0.0
Human toxicity	kg.1,4-DB-eq	2681.3	2673.6	2674.4	2670.5
Photochemical oxidant formation	kg.NMVOC	14.8	14.1	14.1	13.8
Particulate matter formation	kg.PM10-eq	20.0	19.8	19.8	19.7
Ionising radiation	kg.U235-eq	845.0	838.9	839.2	836.0
Terrestrial acidification	kg.SO_2-eq	20.4	19.8	19.7	19.4
Freshwater eutrophication	kg.P-eq	2.0	2.0	2.0	1.9
Marine eutrophication	kg.N-eq	4.7	4.4	4.5	4.3
Terrestrial ecotoxicity	kg.1,4-DB-eq	0.7	0.7	0.7	0.7
Freshwater ecotoxicity	kg.1,4-DB-eq	308.9	308.8	308.8	308.7
Marine ecotoxicity	kg.1,4-DB-eq	322.3	322.0	322.0	321.9
Agricultural land occupation	m^2	104.4	104.2	104.3	104.2
Urban land occupation	m^2	62.5	62.0	62.1	61.9
Natural land transformation	m^2	0.4	0.4	0.4	0.4
Water depletion	m^3	26.8	26.6	26.7	26.6
Metal depletion	kg.Fe-eq	12292.5	12290.1	12290.9	12289.8
Fossil depletion	kg.oil-eq	1239.1	1217.7	1221.0	1210.2

Table 14 Comparison of the characterised results by impact category of the turbine options (per 1t) for the construction stage of the Severn Barrage LCA case study, using Midpoint (H European) Analysis (to 1 decimal place)

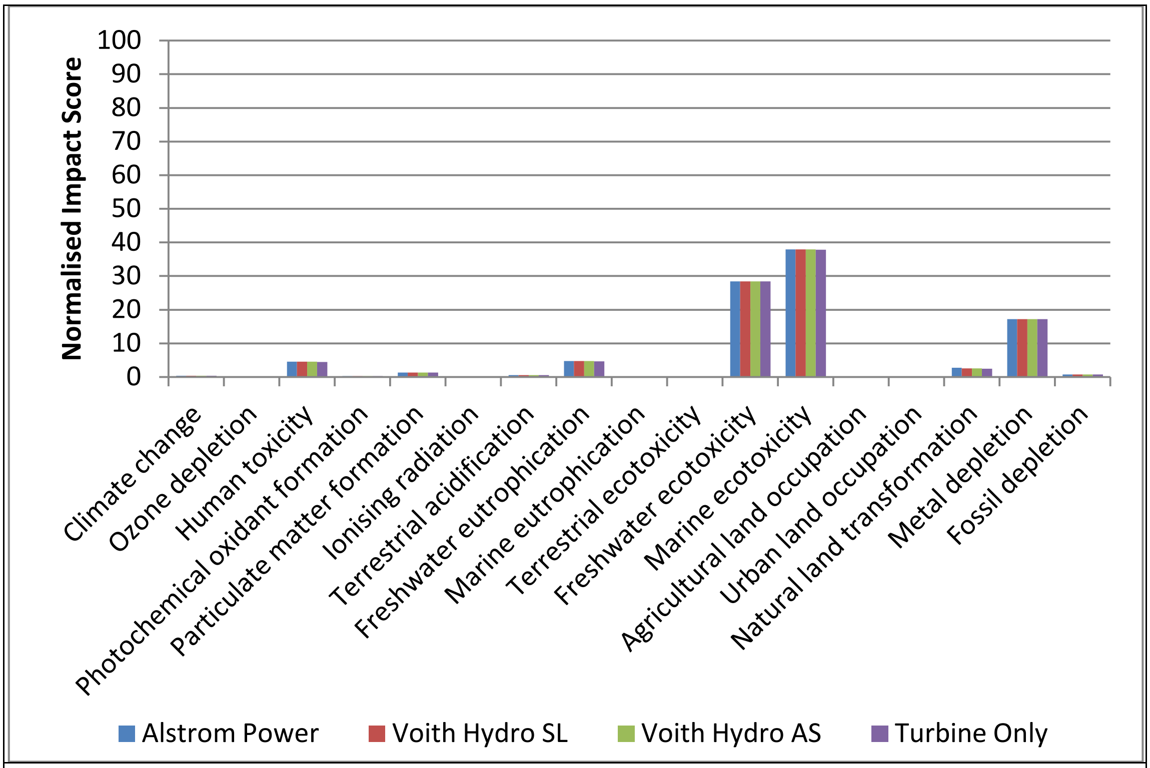

Figure 34 Comparison of the normalised results by impact category for each of the caisson cement options using Midpoint (H European) Analysis

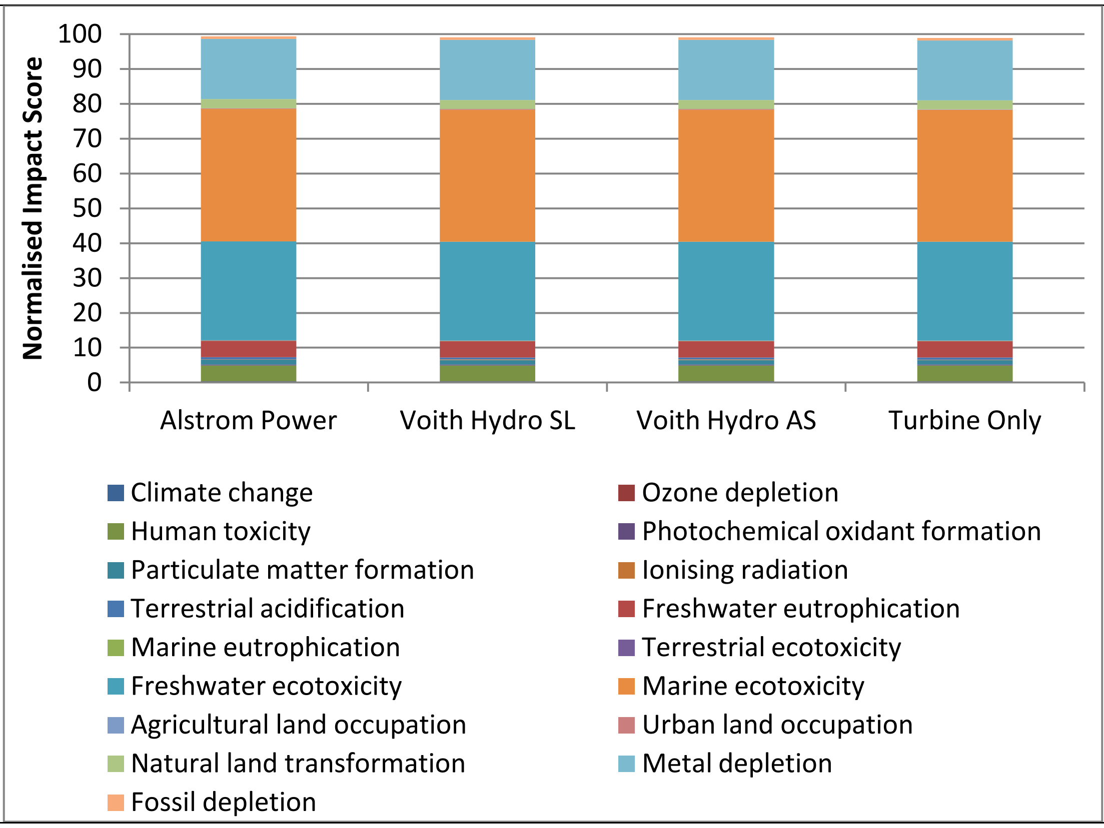

Figure 35 Comparison of the total normalised impact score for each of the caisson cement options, using Midpoint (H European) Analysis

5.4.2.1 Construction in detail

A full set of total characterised results for the construction stage is presented in Table 15 in Section 5.6. Figure 36 shows the total normalized results for the construction inventory per impact category and delineated by component for the 'initial' case model of the Severn Barrage, with the possible range of error. In the normalized context, the largest impact is in the category of natural land transformation. In the 'initial' case, the largest contributor to natural land transformation is from the channel dredging showing that the largest transformation is at the Barrage site itself. However, the large error bar shows that if local source of limestone were insufficient for the rock and aggregate demands and material was sourced from the igneous mine in Glensanda, Scotland, these components would dominate the impact on natural land transformation. It is also this material option which is responsible for the large range in the category of particulate matter formation, which is a minimal impact in the 'initial' and 'best' cases. The next three significant normalized impact categories, that of freshwater ecotoxicity, marine ecotoxicity and metal depletion, are dominated by the contribution from the turbines. As the turbine options vary very little in impact the error bars on these three impact categories vary very little also.

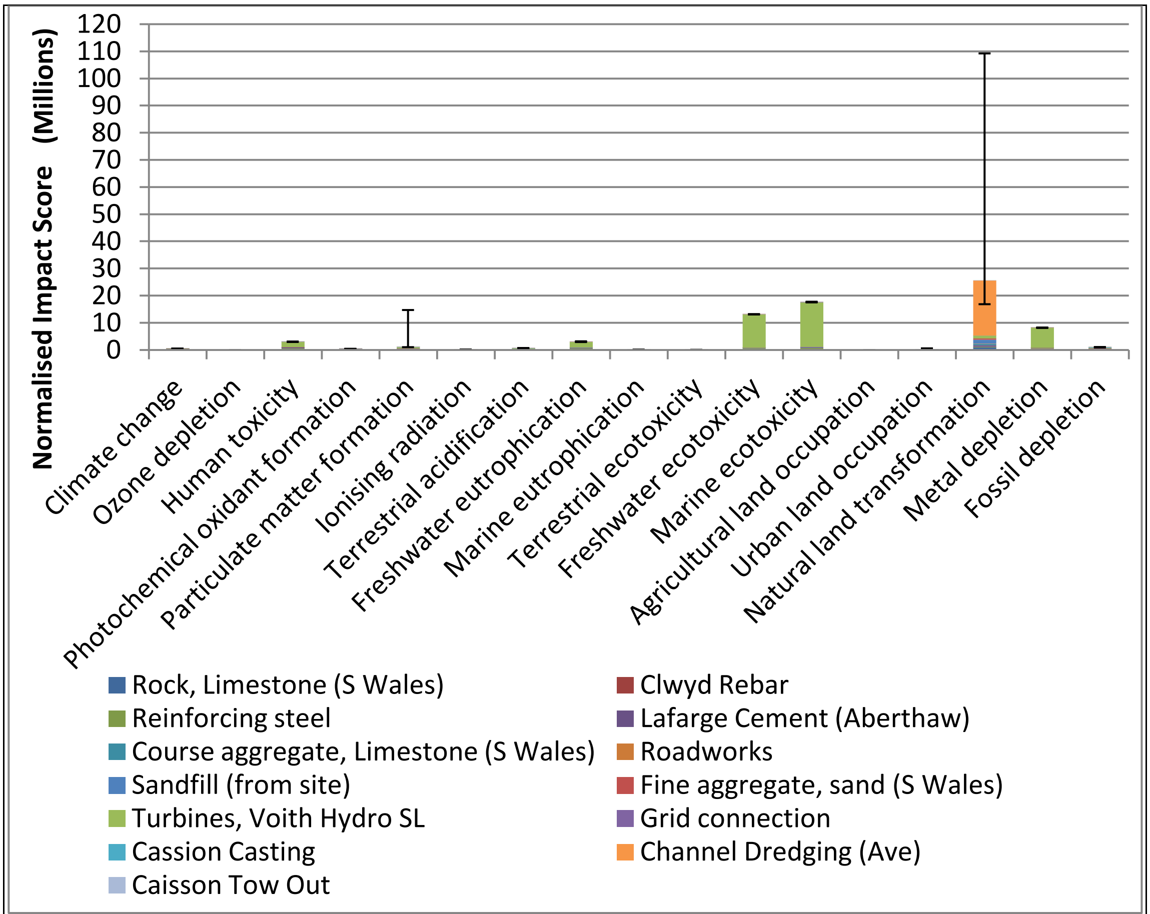

Figure 36 Normalised results by impact category for the construction stage of the Severn Barrage 'initial' case with potential error range using Midpoint (H European) Analysis

Figure 37 shows the same results as Figure 36 but with the axes reversed, so the impact per component can by more easily compared. As is suggested by the inventory analysis presented so far, this figure shows that in the 'initial' case the impact of the turbines dominates the overall impact of the construction stage. The total normalized impact score of the turbines is over twice that of the next most significant component, that of the channel dredging and is over 36 times any of the other components (the steel reinforcement bar being the largest contributor of the remaining components). If, however, rock from Glensanda was used to for fill the rock demand for the embankments, then impact of this component would surpass that of the turbines. This shows that although the turbines contribute a large amount to the overall impact of the Barrage construction in all scenarios, the overall impact is most sensitive to the choice of material used for the rock and aggregate demand.

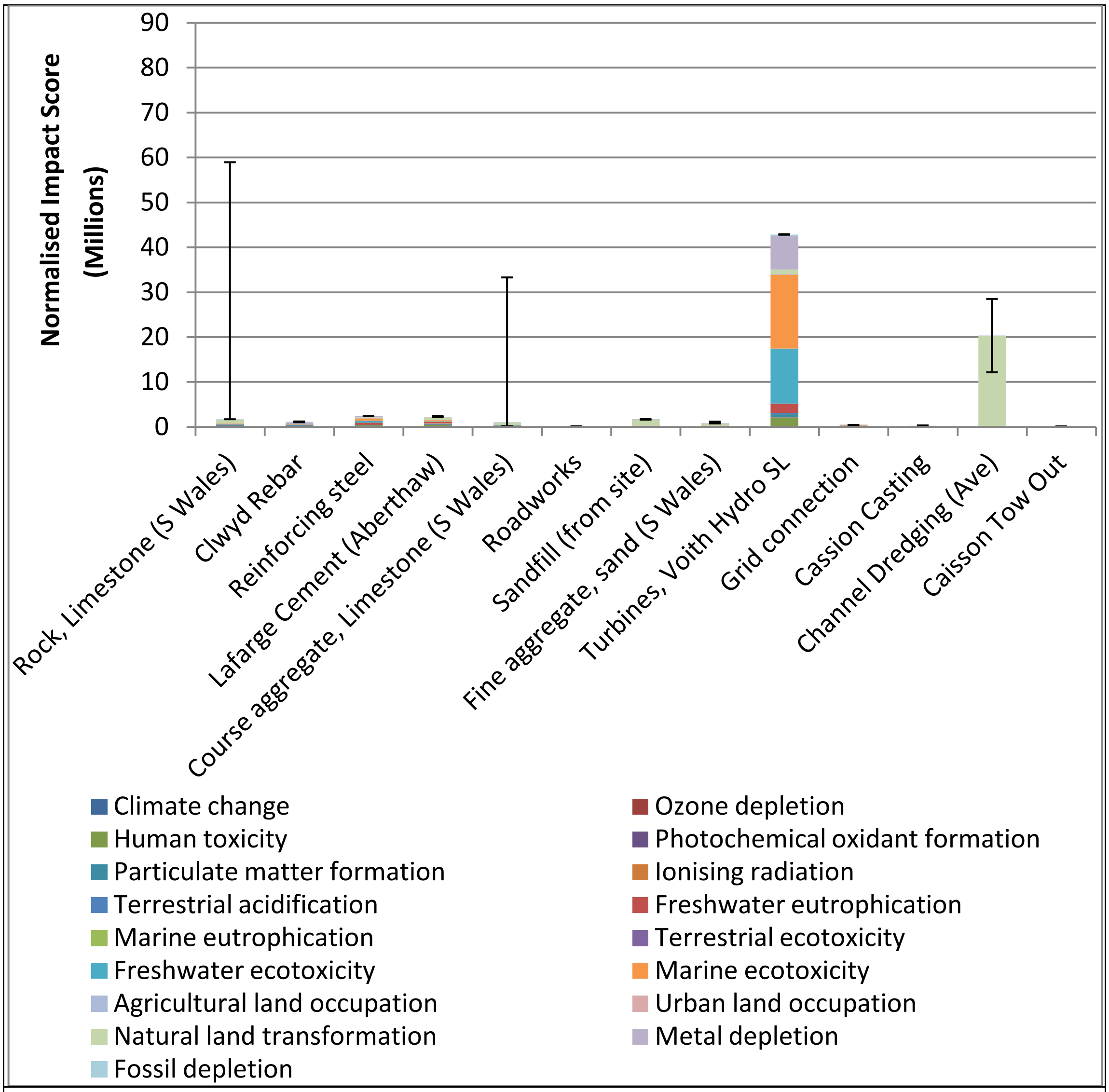

Figure 37 Normalised results by componant for the construction stage of the Severn Barrage 'initial' case with potential error range using Midpoint (H European) Analysis

5.4.3 OPERATION

Aspects included in the analysis of the operation stage are restricted to those activities which occur routinely within the Barrage site over its 120 year lifetime. Any activities that require outside staff or the import of substantial replacement materials are regarded as 'maintenance' and are outlined in Section 5.4.5.

Roberts (Roberts 1982) assumes that annual operational costs would be 1.75% of capital costs and that the operational energy consumption could be calculated on the same basis. This method will predict that the Barrage operation over its lifetime would be 210% more expensive, and hence 210% more energy intensive than the construction stage, and, therefore, the most significant of all the life stages, as shown in the Spevack (Spevack, Jones and Hammond 2011) analysis. However, studies since Roberts' work have generally disregarded the operation stage entirely. Given this large variation in the assumptions applied, investigating the operation stage became a priority. Energy and resource hungry operational processes can be split into the following 2 main areas:

- Direct processes: activities undertaken to directly enable power generation.
- Ancillary processes: energy and resources required for ancillary requirements for running the plant.

5.4.3.1 Direct Processes: 'flood pumping'

The only identified example of an energy hungry direct operational process is 'flood pumping'. This is the proposed method to artificially raise the water level on the basin side prior to the start of generation by temporarily using the turbines as pumps. As there is no suggestion of storing some of the power generated by the Barrage itself to do this, it is assumed that the electricity required to power the turbines in pump mode would be bought from the Grid. However, it has proved very hard to find an explicit calculation of gross energy demand for 'flood pumping' from the available literature. The STPG (Severn Tidal Power Group and the Department of Energy 1989) report states that, "For most of the times during which pumping takes place the required power does not exceed 2 GW." The SDC (Black & Veatch 2007) research report suggests that this power rating is still an appropriate assumption and states that, "...STPG's 2002 proposal for a new appraisal of the project included the study of 1.5 to 2GW of low-head pumped storage...". Figure 20 suggests that pumping would occur for 1 hour in every 12 hour tide cycle, to the nearest hour. Therefore, the total energy demand for 'flood pumping' over the Barrage lifetime was estimated, to the nearest TWh, using:

$$120\ years \times 365.25\ days \times 2\ hours \times 2GW = 175TWh$$

5.4.3.2 Ancillary Processes

The main ancillary operation activities as described in the STPG (Severn Tidal Power Group and the Department of Energy 1989) report are listed below:

- Small scale civil maintenance - major works that would be sub-contracted and not considered a routine operational activity are accounted for as a maintenance activity in this case study,
- Small scale electrical maintenance - major sub-contracted works are considered a maintenance rather than an operational activity in this case study e.g. turbine replacement,
- Locks and navigation services, it is proposed that four tugs are provided on a continuous basis and shipping control facilities are included,
- Small emergency rescue service and medical staff,
- Staff transportation, it is predicted that vehicles would be required for transport between facilities on the Barrage, by self-drive vehicles or by staff bus, and for specialised purposes such as mobile cranes, snow clearance, fire fighting appliances, etc ,
- 24 hour staff canteen,
- Other basic staff facilities e.g. lighting, heating, computers etc.

It is estimated that,

> *"For periods each day when the Barrage is not generating, it will be necessary to purchase power to run the station auxiliaries and Barrage general requirements. The annual mean load has been estimated at 19MW"*, (Severn Tidal Power Group and the Department of Energy 1989).

The parasitic load that the plant operation will place on the plant itself, if any, is unknown, so it was assumed that this was accounted for in the estimated output figures. The electricity consumption will not accurately represent the full energy demand of the plant, let alone the environmental impact. However, obtaining realistic estimates for these types of ancillary activities before the system is in place would be highly speculative and is therefore outside the scope of this assessment. Hence the total lifetime energy demand for ancillary operational processes was estimated, to the nearest TWh, using:

$$120\ years \times 365.25\ days \times 24\ hours \times 19MW = 20TWh$$

This provides a total electricity demand estimate for the operation stage of the Severn Barrage, to the nearest TWh, is given by:

$$175TWh + 20TWh = 195TWh$$

It is necessary to list power bought from the Grid as a separate inventory entry rather than deduct it from the net energy output from the plant as power from the Grid is likely to have a very different environmental impact and energy demand profiles than that of the Barrage itself.

An average mix of generating technologies is assumed for the power bought from the Grid. In reality the technology type actually providing the required power, and hence the impact intensity, could be very specific. It is very possible that if sufficient storage was introduced, the power used to drive flood pumping could actually be provided by the Barrage itself. Conversely, if storage was not addressed this power demand could be met by stand-by fossil fuelled power. Details of this nature are unknown, so it is most appropriate to adopt an average value.

5.4.3.3 Excluded Operational Processes

Impact reduction service provided by sediment deposits: No estimate is made of the carbon benefit resulting from the increased sequestration service provided by the sediment deposits caused by the Barrage. Determining the likelihood of this phenomenon becoming a reality was considered too specialised to fit within the scope of this study. The DECC SEA was the only study to even propose this as a possibility (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors. p 14) so it is in line with the majority of studies to exclude it. The precautionary approach also dictates that it should be assumed that this benefit is not provided.

Changes in traffic behaviour: The installation of a new road crossing along the top of the Barrage could have positive or negative effects. It could reduce the amount of driving done in the UK overall as more people are able to reduce the length of their journey between South Wales and the South West of England or it could encourage more drivers to make the trip who would have otherwise not gone at all. It could even increase the number of visitors driving to the area if the Barrage becomes a tourist attraction. These predictions are also highly specialised and considered outside the scope of this study.

5.4.4 OPERATION: RANGE OF ERROR

If the Barrage is opened in 2025 and operates for its full design life, it will be decommissioned around 2145 at the very earliest. So, over its lifetime, it will draw most of the electricity it requires to operate from a post 2050 National Grid. The UK aspiration is to reduce the carbon emissions of the National Grid considerably, in pursuit of meeting the target to reduce total UK emissions to 80% below 1990 base levels by 2050, and hence it is fair to consider the operational impact assuming that the Grid reduces in impact. It is also feasible to assume a worst case future where measures to decarbonise the National Grid fail and the environmental impact of the National Grid reverts to 1990 levels. This could, for instance, be a scenario in which an increasing UK population who are leading increasingly electrified lifestyles, cause satisfying demand to be prioritised over meeting emission reduction targets. Hence the variability at the operation stage is depended on the assumption of which grid mix will supply the required additional electricity.

The 'initial' case will assume that average annual power supply will be provided by a grid mix equivalent to the 2008 UK National Grid, the 'worst' case by an equivalent 1990 Grid mix and the 'best' case by a hypothetical future Grid equal to the of the Central Control scenario developed by the Transition Pathway work (Hammond, Howard and Jones 2013) as described in section 2.6.1, (the Central Control scenario has the lowest total normalized impact score, or environmental burden, of the three scenarios presented by the Transition Pathways work). As the Roberts method calculates the impact of the operation based on that of the construction stage, it is also subject to a similar range of potential variation i.e. the 'worst' case operation impact is given by 210% of the 'worst' case construction impact and the 'best' case operation impact is given by 210% of the 'best' case construction impact. Figure 38 compares the estimates for energy demand for the operation of the Severn Barrage when it is assumed to be 210% of the construction energy demand, in line with the Roberts study, and against the energy demand of the operational electricity demand calculated in this study, along with the potential ranges and exclusive of energy from natural, 'non-capital' resources. The estimate based on electricity demand is considerably higher than that based on the Roberts method. As the Roberts estimate is based on a cost relationship between two life stages that, in fact, have very different life cycle inventories, the electricity demand method was adopted as the most accurate representation for the operation stage for the overall assessment.

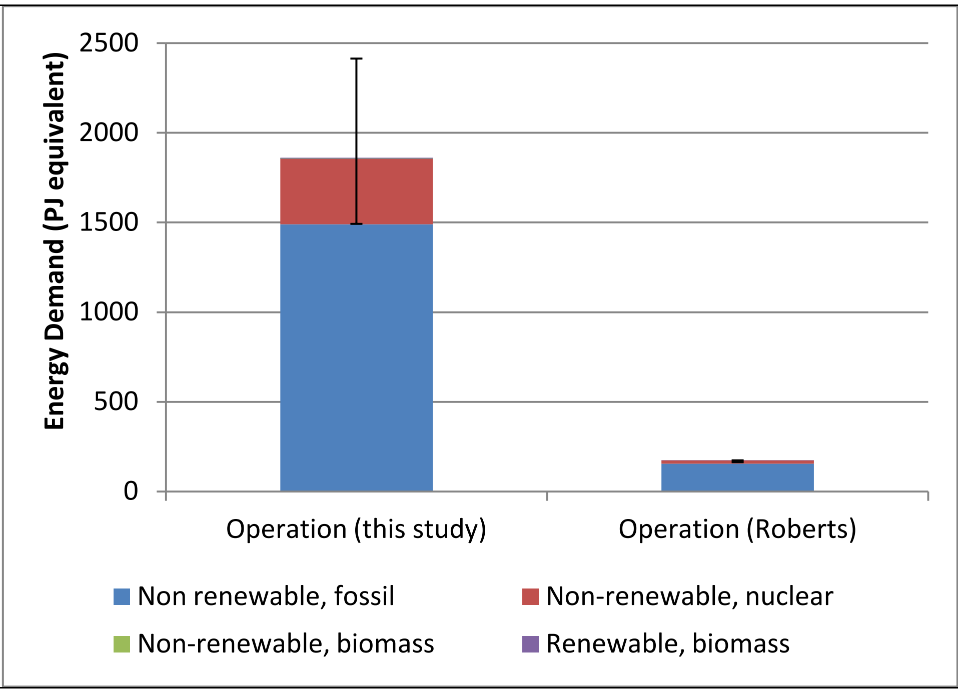

Figure 38 Comparison of energy demand estimates for the operation stage of the Severn Barrage using the Roberts (Roberts 1982) percentage method and the electricity demand re-estimation

5.4.5 MAINTENANCE

Consideration of the maintenance regime is restricted to the turbines only and represented by using estimates regarding the frequency and extent of their replacement. The Roberts report (Roberts 1982) suggests that 70% of the capital cost of the turbines will be incurred in maintaining them every 40 years. However, although it is possible that the raw materials required for maintenance may be less than that required for the capital instillation, it is also possible that it is the cost only that is predicted to be less than that of the capital investment because of, for instance, a maintenance contract arranged with the supplier rather than simply because of a reduced material demand. Hence, in accordance with the precautionary principle, environmental impact associated with the Barrage maintenance is estimated to be equal to twice that of the total impact of the initial turbine instillation i.e. 100% every 40 years after construction over a 120 year life.

5.4.6 MAINTENANCE: RANGE OF ERROR

As maintenance regime is assumed to be made up of the replacing of the turbines, the variability for this stage is proportional to that for the capital contribution of the turbines at the construction stage. From the inventory analysis carried out for the construction stage, it is assumed that the 'initial' case maintenance inventory will be equivalent to twice that of the Voith Hydro SL turbine, 'worst' case will be twice that of the Alstom Power turbine and the 'best' case will be twice that of the Voith Hydro AS turbine.

5.4.7 DECOMMISSION

Due to the long expected life of the Barrage, the method of decommissioning and, hence, the associated environmental impacts are impossible to predict with any certainty. Therefore, the decommissioning stage is excluded from the assessment results, which is in-line with all other previous studies identified. However the end of life options and their impact relative to the other life stages can be speculated upon. The 120 year lifespan is dictated by the specification of the concrete which makes up the barrage itself, the turbines and other electrical components will of course need to be replaced to continue the plant operation within the 120 year lifetime and but this is accounted for. So, assuming that the Barrage ceases to operate as a generating plant after its 120th year the three most likely options in ascending order of probable cost are as follows:

- The plant is abandoned and allowed to disintegrate into the sea. This option would require no additional materials or energy but could have impacts comparable with pollution impacts of disposal via landfill.
- The Barrage becomes an essential flood defence and/or road crossing and the structure is refurbished to prolong its life. This option would require both energy and material input but less than the original construction requirement. Also, refurbishment for a secondary purpose is arguably not allocable to the analysis of the primary purpose, i.e. as an energy generator.
- The materials are removed from site and either recycled or sent to an inland landfill. This would require no additional materials, and would in fact *provide* materials in the recycling scenario. It is estimated that the UK currently recycles 22% of demolition waste and initiatives are in place to increase this percentage (Everett 2009). However the complete removal of the Barrage from site would require approximately as much energy as the 'on site' activities of construction and the transportation of the spoils to either a recycling centre or landfill would have an additional impact. Of course if landfill was adopted instead of recycling there would be no material gain and the potential for associated polluting impacts. However landfill, if implemented appropriately, can sometimes be seen to have a net environmental benefit, as they can be a source of bio-fuel and/or result in large green areas that protected from development.

All of the above options would constitute less than the combined energy and material requirements of the construction stage. Material and energy demand is in fact nil in the case of option 1 and would not be allocable to this study in the case of option 2. Options 1 and 3, in the instance that landfill is adopted for disposal have the potential to release pollutants into the natural environment but could also be accounted for as a environmental benefit as developed land returns to natural land and construction materials return to the land or sea bed from whence they came. Hence, it can be estimated that whichever option is adopted, the decommission stage will have a considerably lower impact than the construction stage

5.5 LIFE CYCLE IMPACT ASSESSMENT RESULTS INTERPRETATION

Table 15 shows the characterised impact results for the three modelled life stages of the Severn Barrage for the 'initial' case and a potential error range generated by the 'best' and 'worst' models. The operation stage is the largest contributor in every impact category. The variation in results is also greatest at the operation stage. The results for the maintenance stage vary very little. This is because the maintenance stage is made up only of a multiple of the turbine capital impact, which only varies with respect to the cradle-to-gate inventory which makes an almost negligible impact compared the impact of the turbine materials, which is identical in all models, see Section 5.4.2.

Impact category	Unit	Construction, 'Initial' case	Construction Range, 'Worst' to 'Best' cases	Operation, 'Initial' case	Operation Range, 'Worst' to 'Best' cases	Maintenance, 'Initial' case	Maintenance Range, 'Worst' to 'Best' cases
Climate change	$t.CO_2eq$	6 520 860.0	6 474 960.0 - 6 142 430.0	109 456 900.0	158 631 000.0 - 17 083 900.0	3 535 510.0	3 579 450.0 - 3 528 710.0
Ozone depletion	t.CFC-11-eq	0.6	0.6 - 0.5	2.8	3.9 - 2.5	0.2	0.2 - 0.2
Human toxicity	t.1,4-DB-eq	1 813 640.0	1 855 460.0 - 1 775 190.0	23 219 800.0	45 329 600.0 - 16 148 700.0	2 310 700.0	2 316 620.0 - 2 309 960.0
Photochemical oxidant formation	t.NMVOC	24 064.8	24 351.2 - 21 533.1	236 326.0	435 416.0 - 125 085.0	12 193.9	12 759.5 -12 176.4
Particulate matter formation	t.PM10-eq	16 482.0	219 865.0 - 15 825.6	112 610.0	242 662.0 - 62 306.4	17 100.1	17 302.4 -17 116.0
Ionising radiation	t.U235-eq	805 144.0	890 022.0 - 768 945.0	35 345 600.0	49 701 100.0 - 58 596 900.0	725 082.0	730 062.0 - 724 809.0
Terrestrial acidification	$t.SO_2$-eq	23 016.6	25 624.5 - 21 544.3	366 251.0	844 141.0 - 165 231.0	17 036.3	17 637.8 - 17 121.6
Freshwater eutrophication	t.P-eq	1 253.3	1 339.3 - 1 226.4	32 387.9	65 018.3 - 15 322.2	1 688.1	1 694.2 - 1 688.1
Marine eutrophication	t.N-eq	1 066.5	1 098.0 - 977.0	16 388.9	30 939.9 - 8 054.1	733.9	754.5 - 733.5
Terrestrial ecotoxicity	t.1,4-DB-eq	565.7	536.7 - 528.2	1 905.4	5 204.5 - 29 543.0	596.3	601.6 - 594.7
Freshwater ecotoxicity	t.1,4-DB-eq	143 238.0	144 136.0 - 142 503.0	498 443.0	987 783.0 - 259 112.0	266 799.0	266 925.0 - 266 782.0
Marine ecotoxicity	t.1,4-DB-eq	150 030.0	151 290.0 - 149 208.0	529 710.0	998 643.0 - 278 506.0	278 228.0	278 426.0 - 278 228.0
Agricultural land occupation	km^2	69.9	70.4 - 68.2	1 494.9	3 054.5 - 4 254.5	90.1	90.2 - 90.1
Urban land occupation	km^2	58.5	258.1 - 55.8	489.5	943.5 - 292.9	53.7	54.0 - 53.6
Natural land transformation	km^2	4.1	17.6 - 2.7	23.0	16.6 - 9.4	0.4	0.4 - 0.4
Water depletion	km^3	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.0	0.0 - 0.0
Metal depletion	t.Fe-eq	5 870 400.0	5 858 690.0 - 5 857 340.0	541 499.0	727 907.0 -1 334 540.0	10 619 300.0	10 620 700.0 - 10 618 700.0
Fossil depletion	t.oil-eq	1 755 170.0	1 734 030.0 - 1 644 380.0	35 479 900.0	45 020 520.0 - 16 450 300.0	1 054 940.0	1 070 620.0 - 1 052 060.0

Table 15 Characterised results by impact category of the life cycle stages of the Severn Barrage, using Midpoint (H European) Analysis (to 1 decimal place)

The total normalized lifetime impact score of the Severn Barrage is estimated to be 592 million in a range of 910 - 371 million. That gives a score of 5 million in a range of 8 – 3 million per year of life. This means that the Barrage scheme has an emission rate approximately equivalent to 5 million average European citizens which is roughly the population Norway.

Figure 39 shows the normalised impact scores of the whole Severn Barrage model according to impact category and includes error bars which depict the potential range of scores, from 'best' case to 'worst' case. Figure 40 shows the same data as that shown in Figure 39 but arranged according to life stage rather than by impact category so that the life stages can be compared more easily. As was shown by the characterised results, the biggest contribution to the overall environmental impact in the normalized context is also from the operation stage, which also has the greatest range of error. Hence design variations in the other two stages of construction and maintenance have very little effect on the overall impact. Even if the most impactful construction materials and methods were implemented, the impact would still be less than the best case operational method. This is not only because the annual operational electricity demand of the Barrage is substantial, particularly compared to most other energy plants, but it is also, due to the very long expected life time of the Barrage. Over 120 years, it is not surprising that the cumulative annual impact of operational activities out strips that of the one-off or infrequent activities of construction and maintenance. This large operational impact was, however, ignored in some of the existing analyses reviewed (Black & Veatch 2007) (Woollcombe-Adams, Watson and Shaw 2009). This is probably due to a failure to acknowledge the proportion of the operational electricity demand that would not be met by the plant itself, as would normally be the case for an energy generation plant, nor the consequences of that inventory subtlety.

Clearly then, the design life is a key assumption in estimating the lifetime impact of the Barrage. As the dominant life stage is that of operation, the total impact estimate will vary proportionally with that of the assumed lifespan. This relationship would only be broken in the case that the lifespan is assumed so short that the construction phase becomes dominant but it can be assumed that any design that considered viable would have to have a life expectancy long enough for this never to be the case. This proportional variation does, however, mean that the rate of impact per year of life or, more importantly to this research, per unit of power generated would not be significantly changed.

The total impact associated with decommissioning was estimated to be considerably less than that of construction, see Section 5.4.7. Given that the construction stage itself has been shown to be a minor contributor to the overall impact, it can now be estimated that the impact of the decommissioning stage would make negligible difference if it were included in the analysis.

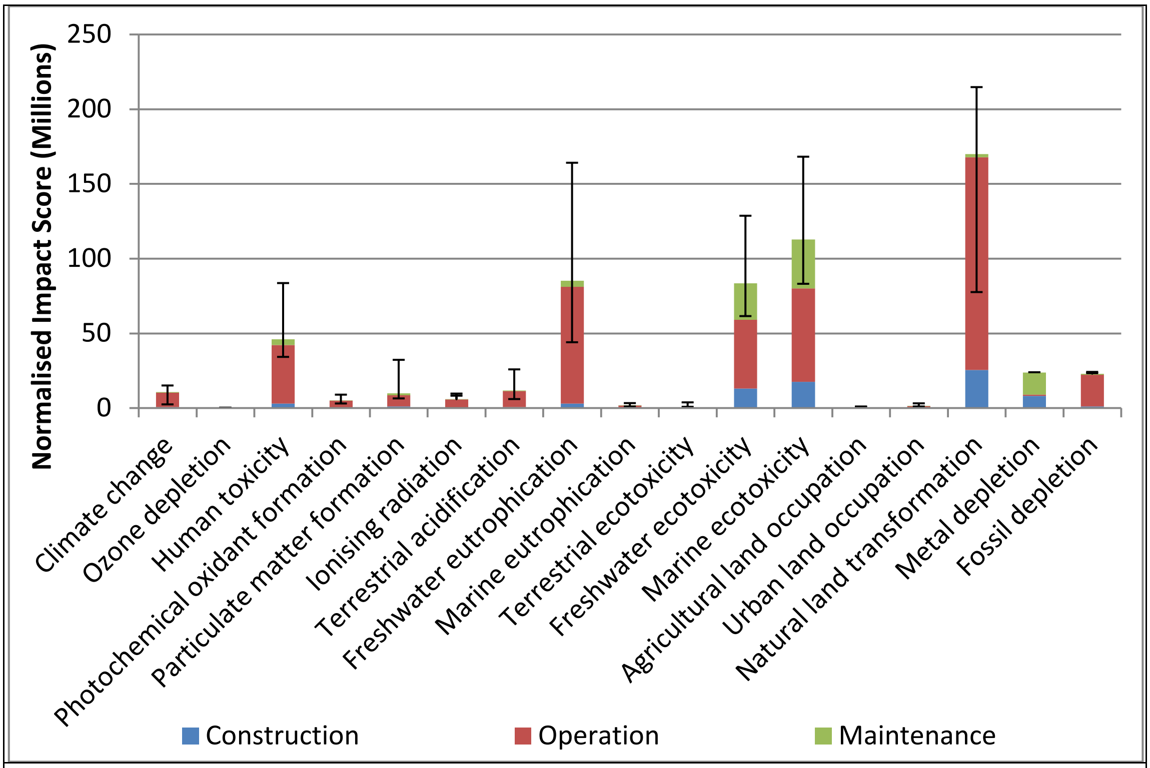

Figure 39 Normalised results by impact category for each of the modelled life stages of the Severn Barrage, including the possible range of scores, using Midpoint (H European) Analysis

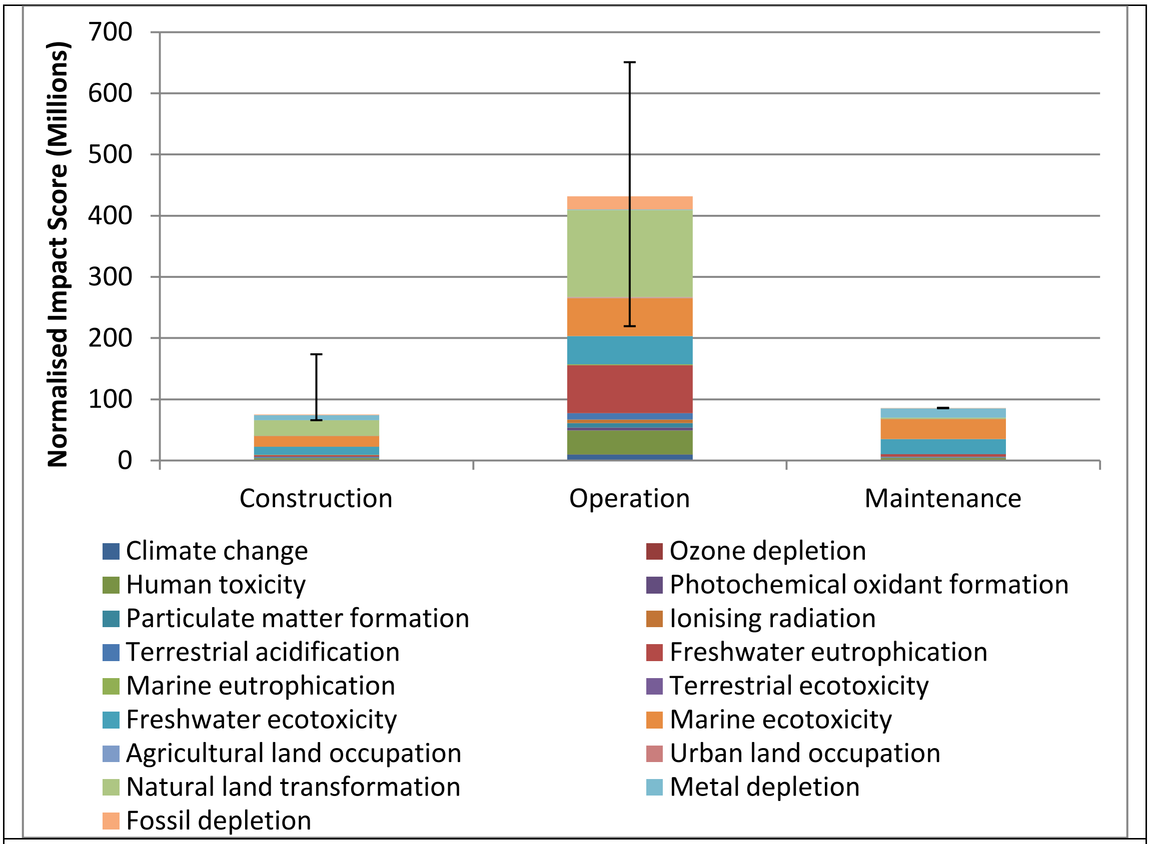

Figure 40 Normalised impact results for by life stage for the Severn Barrage, including the possible range of scores, using Midpoint (H European) Analysis

5.5.1 CARBON ANALYSIS

Figure 41 shows the contribution to total GWP from the three modelled life stages of the Barrage, as presented in Table 15. Again, the error bars show the potential variation depending on which inventory options are selected. The total carbon equivalent emissions are estimated at 120 Mt.CO_2 (equivalent) but the range of error stretches from 27 - 169Mt.CO_2 (equivalent). For reference, that is approximately between 5 and 34 times that of the SDC estimate (Black & Veatch 2007), between 1 and 9 times that of the Spevack estimate (Spevack, Jones and Hammond 2011) and between 1 and 4 times the maximum DECC estimate (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010), see Table 24 for a summary comparison of the results.

The large increase in estimated lifetime GWP compared to previous studies is due to the re-estimated value for the operational electricity demand. The proportional contribution to the overall GWP from the operation stage is greater than that of its contribution to the overall lifetime normalized impact score. This shows that electricity generation has a higher GWP over other environmental impacts when compared to building materials and construction and maintenance activities. Despite the very large variation in the GWP of the operational stage, the minimum estimated value for this stage is greater than the maximum estimated value of either of the other two modelled stages. The maximum estimated value for the GWP of the construction stage is actually given in the 'initial' case because the largest contribution to this impact in the construction stage is from the 'local' limestone, used for rock and coarse aggregate. The rock from Glensanda which has a greater environmental impact overall, and is therefore regarded as the 'worst' choice, actually has a lower GWP. The GWP difference between these two construction materials is due to the difference in transportation, as discussed in Section 5.4.2.

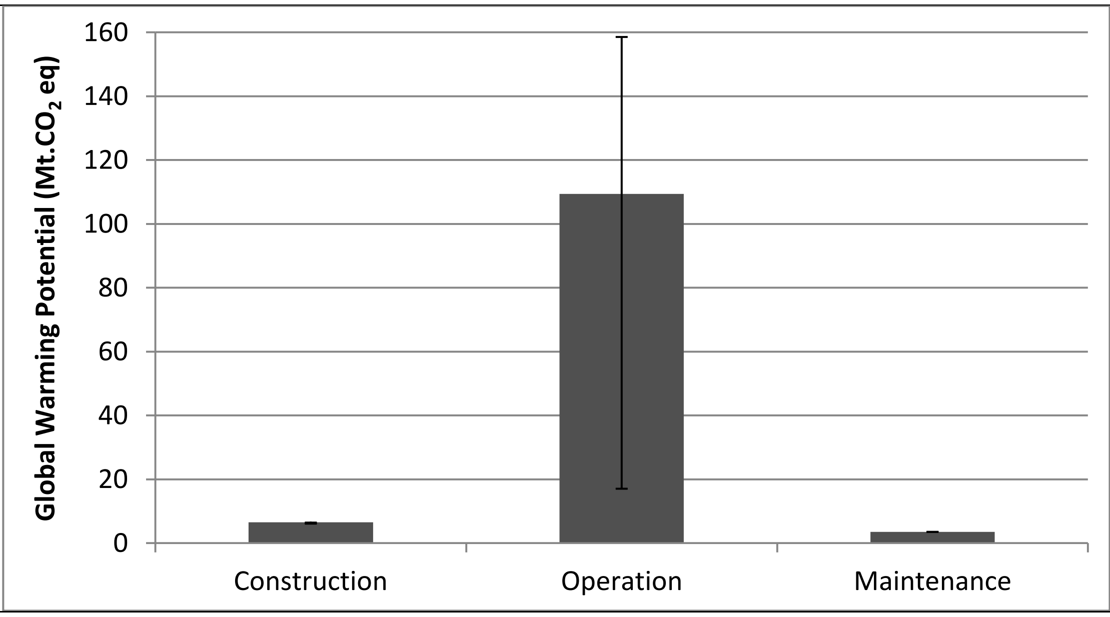

Figure 41 Global warming potential (expressed in Mt.CO_2eq) by life stage for the Severn Barrage, including the possible range of scores

The variation in GWP at the operation stage is very large, the difference between the 'best' and the 'worst' case models is greater than the total estimate for the operational stage of the 'initial' case. The operation stage consists entirely of electricity drawn from the National Grid so the associated carbon (equivalent) emissions depend on what National

Grid mix is assumed. Table 16 shows the total specific normalized impact and GWP per MWh for the range of representations for the UK National Grid mix used in this study (Hammond, Howard and Jones 2013). The carbon emissions per MWh of electricity varies much more than the total normalized environmental impact across the range of National Grid mixes is adopted, and this shows why the total GWP estimate for the Severn Barrage has a wider range of error than that of the estimate for total normalized environmental impact. Table 16 also shows the specific energy demand per MWh of the National Grid representations and that these vary proportional less than either the normalized impact or the GWP. Hence, as will be shown in the next section, the overall energy demand of the operational stage will vary less than the two impact indicators already discussed.

	UK National Grid 1990, baseline	UK National Grid 2008	UK 2050 - Central Control V1.1	UK 2050 Market Rules - V1.1	UK 2050 - Thousand Flowers V1.1
Normalised environmental impact (score/MWh)	3.3	2.2	1.1	1.6	1.2
GWP (kg.CO_2eq/MWh)	812.2	560.4	87.5	111.8	96.5
Energy (MJ/MWh)	12 358	9 527	7 637	8 547	8 719

Table 16 Comparison of specific impacts for different representation of the UK National Grid mix (Hammond, Howard and Jones 2013)

5.5.2 ENERGY ANALYSIS

Table 17 shows the characterised energy demand results for each of the three modelled life stages with a potential range of error for the Severn Barrage. As might be expected given that the operation stage is represented by an energy demand only, the operation stage has the highest energy demand of the modelled life stage from every energy resource calculated. The 'best' case operational energy demand actually exceeds that of the 'worst' and 'initial' cases in the resource categories of nuclear energy, renewable biomass and the natural resource categories of renewable wind, solar, geothermal and renewable water. This is because the future hypothetical National Grid mix which is proposed to supply the Barrage in the 'best' case, that of the Central Control mix developed by the Transition Pathways work, assumes a large increase in the utilization of these types of low carbon energy resources. The reduction in demand from fossil fuel, however, is more than enough to compensate for the increases from low carbon resources so the total operational energy demand in the 'best' case is still less that in either the 'worst' or 'initial' cases. The largest fossil fuel demand at the construction stage is in the 'initial' case. This is, as in the analysis of the GWP, due to the transportation differences between the 'local' limestone used for rock and coarse aggregate in the 'initial' case and the Glensanda rock alternative used in the 'worst' case, see Section 5.4.2. One large energy resource that is not included in Table 17 is that provided by the tide itself. However, as discussed in section 3.5.3, for energy analysis of renewable energy schemes it is inappropriate to include natural energy resources of this sort in the capital energy demand, the energy 'in', to which the generated energy returns, the energy 'out', are compared. This is also true of the two natural energy resources that are included in Table 17, that of renewable wind, solar, geothermal and renewable water. Results for these categories are shown in Table 17 for completeness but will be excluded from the remaining result analysis presented. .

Impact category	**Unit**	**Construction - 'Initial' case**	**Construction Range - 'Worst' to 'Best' cases**	**Operation - 'Initial' case**	**Operation Range - 'Worst' to 'Best' cases**	**Maintenance - 'Initial' case**	**Maintenance Range - 'Worst' to 'Best' cases**
Non renewable, fossil	TJ	73 733	72 846 - 69 076	1 489 735	1 890 198 - 690 710	44 294	44 953 - 44 173
Non-renewable, nuclear	TJ	8 113	8 959 - 7 751	366 726	515 464 - 608 713	7 373	7 424 - 7 371
Non-renewable, biomass	TJ	0	0	1	1 - 0	0	0
Renewable, biomass	TJ	378	400 - 367	4 316	7 870 - 192 124	496	498 - 496
Renewable, wind, solar, geothermal	*TJ*	*93*	*108 - 91*	*14 712*	*534 - 231 632*	*136*	*137 - 136*
Renewable, water	*TJ*	*4 867*	*5 080 - 4 792*	*12 383*	*16 663 - 58 080*	*7 782*	*7 789 - 7 781*

Table 17 Lifetime energy demand per energy resource category by life stage for the Severn Barrage (to the nearest TJ)

Figure 42 shows the total energy demand estimate for the three modelled life stages of the Barrage. The error bars show the potential variation depending on the assumptions made in the LCA modelling. It can be seen that the energy contribution from renewable and non-renewable biomass is negligible. As might be expected, the proportional distribution of the energy demand across life stage echoes that found in the environmental impact and carbon analyses and the largest contributor overall is the operation stage. However, as predicted, the range of error is much less in this case because of the reduced range in energy demand across the National Grid representations. This is really because the energy required to make electricity cannot be substantially altered. What can be changed, however, is the proportion of that energy is drawn from natural resources and, hence, the proportion of that energy that it is appropriate to include in the energy demand calculation. This is explains the smaller but still very apparent variation. It must also be remembered that even though the total energy demand for the operational stage varies relatively little, compared to the other impact indicators already discussed, the mix of energy resources that make up the extreme cases do vary a great deal.

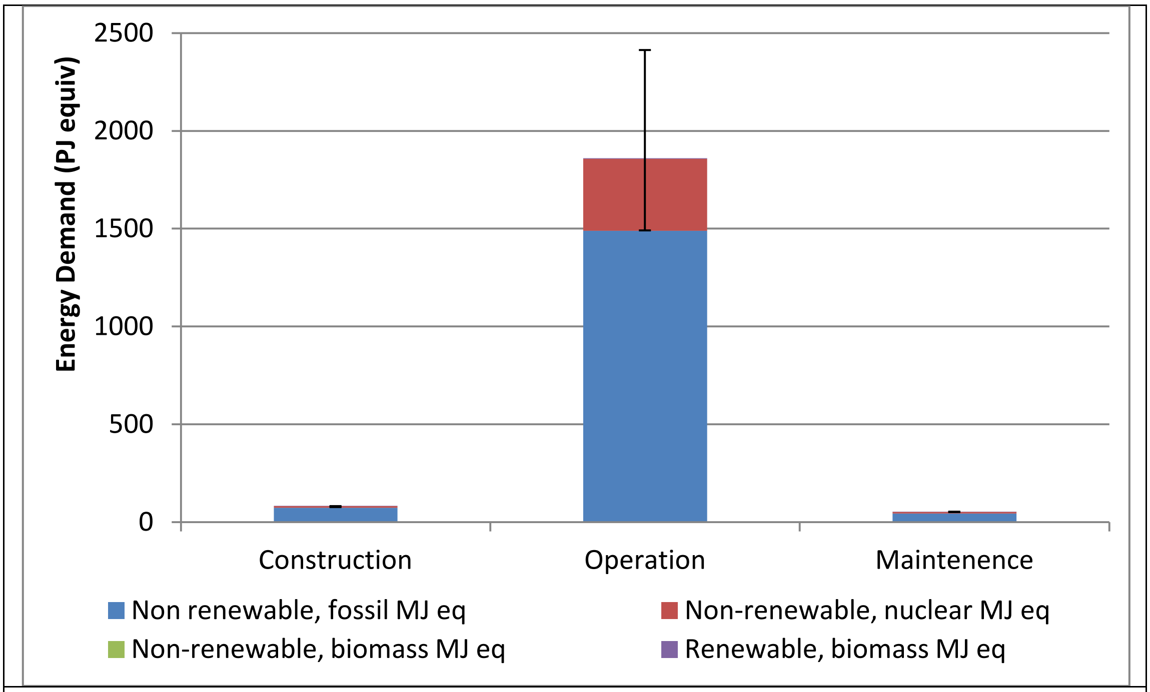

Figure 42 Energy demand of the Severn Barrage by life stage, including the possible range of scores

The total lifetime energy demand estimate is 1,995,200 TJ, in a possible range error of 1,620,800 TJ to 2,548,600 TJ, exclusive of decommissioning. These estimates are between 4 and 8 larger than that estimated by Spevack (Spevack, Jones and Hammond 2011). Table 18 compares the energy results for the three modelled life stages from the two studies. The large difference can be almost entirely attributed to the different assumptions adopted for the estimation of the operation stage i.e. that the Spevack analysis is based on estimates taken from Roberts' work and this study has re-estimated the electricity requirement based on demand figures found in the STPG report (Severn Tidal Power Group and the Department of Energy 1989). Although the greatest difference is at the operational stage, there is also a large difference in at the maintenance stage. Both studies assume that the maintenance demand is represented by a multiple of the capital demand of the turbines only, however Spevack adopts the Roberts finance based proportion of 70% of capital demand per maintenance episode (so 140% over the full 120 lifespan) whereas this study uses 100% of capital demand per episode (so 200% over the full lifetime) but perhaps more significantly the capital demand estimate in this study, itself, is around 2.5 times that made in the Spevack. It is not clear from the data presented so far from the Spevack study why this should be but it could be because this study assumes that the steel component of the turbines are made from chromium steel whereas the Spevack study probably assumes a less energy intensive material type. Chromium steel is adopted in this study because it seems highly likely that an extensively treated steel of some kind, if not actually chromium, would be required to withstand 40 years of salt water, also using a higher energy steel is in line with the precautionary approach.

	Construction Energy (TJ)	Operation Energy (TJ)	Maintenance Energy (TJ)
Spevack et al (Spevack, Jones and Hammond 2011)	101 130	212 360	15 120
This study, 'initial' case	82 224	1 860 777	52 164
Error range, 'worst' to 'best' cases	82 205 - 77 195	2 413 533 - 1 491 547	52 875 - 52 040

Table 18 Comparison of energy estimates by life stage with the Spevack estimates

5.5.2.1 Energy Gain Ratio

The annual estimated power output for the Severn Barrage is 17 TWh (Severn Tidal Power Group and the Department of Energy 1989), which is equivalent to 61 PJ. Assuming the Barrage does operate at this average annual output for its design life of 120 years, its total lifetime output would reach 7,320PJ. As already stated, the total lifetime energy demand of the Barrage is 1,995,200 TJ, in a possible range error of 1,620,800 TJ to 2,548,600 TJ. This gives an energy gain ratio, EGR, of 3.6, in a possible range of 2.8 to 4.5. All these estimates are well over 1 showing that the Barrage will generate more energy than it demands. Of course, the Barrage cannot defy the second law of thermodynamics so it is worth noting that if the energy provided by the tide was included in the energy demand estimate the EGR would be less than 1 but, as already discussed, for the purposes of this study it is not appropriate to include natural energy of that kind in the total demand estimate.

Although an EGR that is simply more than one is considerably better than 'conventional' energy generating technologies, a score of 4.5 or less does not compare very well with those estimated for other renewable energy systems. A review of studies carried out for a range of on and off shore wind turbines showed that wind energy has a minimum EGR of 6.7 and can be as high as 71.4 (Lenzen and Munksgaard 2001). Within marine power systems, the *Pelamis* wave device has been shown to have an EGR of 12.3 (Parker, Harrison and Chick 2007) and the EGR of the SeaGen tidal stream device has been estimated at 13.2 (Douglas, Harrison and Chick 2007).

5.5.2.2 Energy Payback Period

Figure 43 shows the cumulative energy generation for the first 50 years after the plant becomes fully operable and the points at which the lifetime energy demand of the Severn Barrage is 'paid back'. As is shown, the Severn Barrage is estimated to payback its lifetime energy demand in 33 years from commissioning, in a range of 42 to 27 years. All these payback periods are less than half the design life of the plant, and the 'initial' and 'best' case payback times are less than a third.

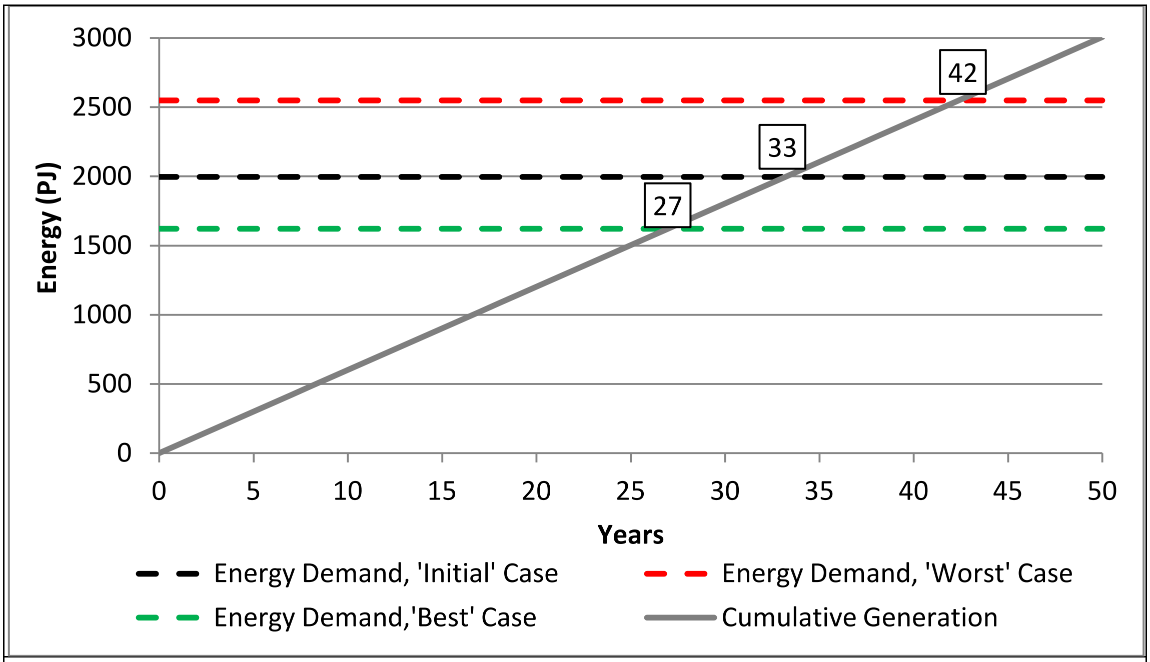

Figure 43 Plot of energy payback periods for the Severn Barrage for a range of options

5.5.2.3 Energy Results Comparison with the existing analyses reviewed

Although the EGR and energy payback periods calculated are extremely good for an energy generation plant, they far exceed those found in the existing literature, see section 4.7. Table 19 compares the total estimated lifetime energy demand, the energy payback period and the EGR for Severn Barrage as estimated in this study with those found in the existing energy analyses reviewed. The differences in energy metric results can be accounted for by the increased detail in the operation energy estimate in comparison to studies that have been completed previously. The majority of the operational demand is for the 'flood pumping'. Neither the Roberts nor the Spevack studies expressly say whether the power demand for 'flood pumping' is included in their estimates. However, the modelling studies reviewed (Black & Veatch 2007) (Severn Tidal Power Group and the Department of Energy 1989) suggest that the assumed power output of 16.8 TWh in the case of Spevack, would not be obtained without 'flood pumping', therefore the study results must be regarded as inclusive of 'flood pumping'. The Roberts study was completed before the subtleties of operational modes had been explored, however the similarities between the Roberts results and the Spevack results imply that it is justified to regard the Roberts results as being inclusive of 'flood pumping'. Hence the results found in this study are more thorough and therefore more realistic than those published so far.

	Total Lifetime Energy Demand (TJ)	Energy Gain Ratio	Energy Payback Period (Years)
Roberts (Roberts 1982)	358 000	12 - 16	8.3
Spevack et al (Spevack, Jones and Hammond 2011)	328 610	18 - 26	8.6
This study - 'initial' case	1 995 165	3.6	33
Error range - 'worst' to 'best' cases	2 548 613 -1 620 782	2.8 - 4.5	27 - 42

Table 19 Comparison of energy results with those from the existing analyses reviewed

5.6 LIFE CYCLE ASSESSMENT RESULTS INTERPRETATION: POWER IN CONTEXT

In order to make a meaningful comparison of between the Cardiff-Weston Tidal Barrage and other electricity generating options, we need to resolve the impact with an easily comparable 'functional' unit, i.e. 1 MWh. This was defined using the following:

$$\frac{Total\ Life\ Cycle\ Impact}{Total\ Lifetime\ Electricity\ Output\ (MWh)}$$

The design life of the Barrage is 120 years and the annual power output is 17 TWh (Severn Tidal Power Group and the Department of Energy 1989) so the total lifetime electricity output can be assumed to be 2040 TWh. The resultant characterised results for each impact category per 1MWh of power generated are presented in Table 20.

Impact category	Unit	Severn Barrage - 'Initial' case	Error range - 'Worst' to 'Best' cases
Climate change	kg.CO_2eq/MWh(e)	59	83 - 13
Ozone depletion	kg.CFC-11-eq/MWh(e)	0	0
Human toxicity	kg.1,4-DB-eq/MWh(e)	13	25 - 11
Photochemical oxidant formation	kg.NMVOC/MWh(e)	0	0
Particulate matter formation	kg.PM10-eq/MWh(e)	0	0
Ionising radiation	kg.U235-eq/MWh(e)	18	26 - 30
Terrestrial acidification	kg.SO_2-eq/MWh(e)	0	0
Freshwater eutrophication	kg.P-eq/MWh(e)	0	0
Marine eutrophication	kg.N-eq/MWh(e)	0	0
Terrestrial ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0
0Freshwater ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	1 - 0
Marine ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	1 - 0
Agricultural land occupation	m^2/MWh(e)	1	2 -2
Urban land occupation	m^2/MWh(e)	0	1 - 0
Natural land transformation	m^2/MWh(e)	0	0
Water depletion	m^3/MWh(e)	0	0
Metal depletion	kg.Fe-eq/MWh(e)	8	11 - 12
Fossil depletion	kg.oil-eq/MWh(e)	19	24 - 10

Table 20 Specific characterised results by impact category for the power generated by the Severn Barrage, using Midpoint (H European) Analysis (to the nearest whole unit)

Figure 44 compares the normalised impact score per 1MWh of the Severn Barrage, with the potential range of error shown, to that of models of the UK National Grid mixes taken from the Transition Pathways Whole Systems work (Hammond, Howard and Jones 2013). It can be seen that even in the 'worst' case, the specific environmental impact of electricity generated by the Severn Barrage would be less than a half of the lowest impact scenario for the UK National Grid, that of the Transition Pathways Central Control scenario in 2050.

It appears, however, that the proportional spread of impacts across the suite of categories included for the Severn Barrage is extremely similar to all National Grid representations. This is not surprising because, as discussed, the overall impact of the Severn Barrage is almost entirely made up of its electricity demand at the operation stage.

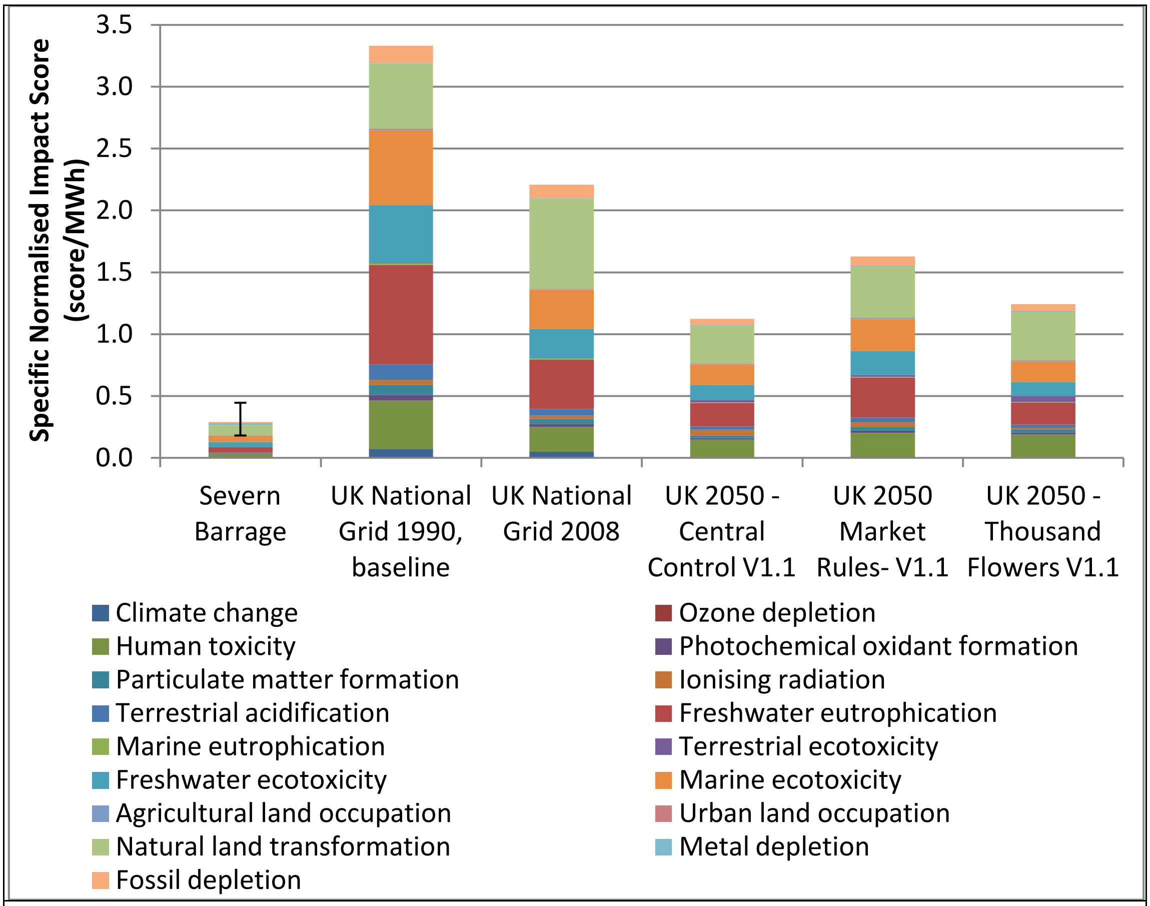

Figure 44 Comparison of specific normalised scores of the Severn Barrage with that of the UK National Grid, using Midpoint (H European) Analysis, using Midpoint (H European) Analysis

5.6.1.1 Displaced Environmental Impact Payback Period

With these specific impact results, the displaced impact payback period of the Severn Barrage can be estimated using:

$$\frac{Life\ Cycle\ Impact\ for\ Severn\ Barrage}{Annual\ Power\ Output \times (Specific\ Impact\ of\ Grid - Specific\ Impact\ of\ Severn\ barrage)}$$

Table 21 presents the displaced environment payback results against each of the five National Grid mixes modelled (Hammond, Howard and Jones 2013), using the total normalized impact score to represent total environmental impact. For every modelled option of the Severn Barrage and against every representation of the National Grid displaced, the impact savings made would offset the total lifetime impact of the Severn Barrage well within its design lifetime. It should also be noted that it is most realistic to assume that the Barrage displaces the same National Grid mix that supplies it. Hence the most realistic displaced payback periods are the 'worst' case against the 1990 baseline mix, the 'initial' case against the 2008 mix and the 'best' case against the Central Control 2050 mix. This reduces the overall potential range of displaced impact payback periods to 24 to 18 years, which is less than a quarter of the design lifespan.

	Displaced payback period for the Severn Barrage - 'Initial' case	Error range - 'Worst' to 'Best' cases
UK National Grid 1990, baseline	12	19 - 7
UK National Grid 2008	18	31 - 11
UK 2050 – Central Control V1.1	43	80 - 24
UK 2050 – Market Rules V1.1	26	46 - 15
UK 2050 – Thousand Flowers V1.1	37	68 - 21

Table 21 Set of displaced impact payback period results for the Severn Barrage (to the nearest year)

5.6.2 SPECIFIC CARBON

The GWP per 1MWh of power output for the Severn Barrage was estimated at 59 kg.CO_2 (equivalent), with a range of 83 to 13 kg.CO_2 (equivalent), see Table 20. The SeaGen tidal stream device and the *Pelamis* wave device have estimated life cycle carbon intensities of 15 kg.CO_2/MWh (Douglas, Harrison and Chick 2007) and 23 kg.CO_2/MWh (Parker, Harrison and Chick 2007) respectively, so the Severn Barrage is comparable to other marine power options in the best case. However it compares extremely favourably with the estimates made for the overall UK National Grid mix. From the values presented in Table 16, it can be seen that in all cases the specific GWP of the National Grid mix exceeds that of the Severn Barrage. Figure 45 compares these estimates, including the potential range of error for the Severn Barrage. This suggests that the electricity generated by the Severn Barrage will provide a carbon saving in comparison with the National Grid, at least until 2050. The relative carbon saving is, however, much less than the normalized impact saving. This is because the future scenarios developed by the Transition Pathways team (Hammond, Howard and Jones 2013) are optimised for low carbon generation rather than low impact or even low energy generation. For instance, the Market Rules scenario has a high proportion of coal fired energy generation with CCS, this explains why its specific GWP is just less than a twice that of the Severn Barrage 'initial' case while its specific normalized impact score is almost six times as much.

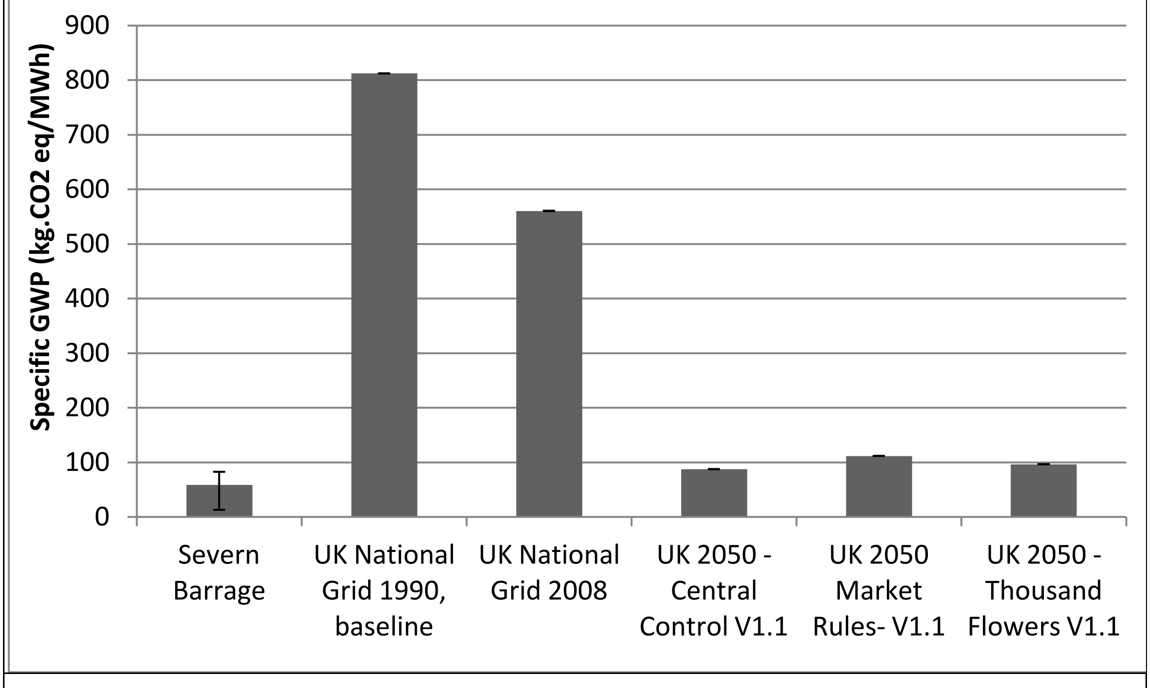

Figure 45 Comparison of the specific GWP of the Severn Barrage with that of the UK National Grid

The carbon (equivalent) savings available per 1MWh against the five National Grid models are presented in Table 22. As already shown in Figure 45, there are carbon savings available irrespective of which Severn Barrage option is compared to which National Grid representation. Again, the most realistic range is actually indicated by the saving made by the 'worst' case Severn Barrage against the 1990 baseline Grid and the 'best' case against the Central Control 2050 Grid. This eliminates the largest and the smallest savings estimates, giving the slightly reduced range of 730 to 74 kg.CO_2 (equivalent) per 1MWh generated. Arguably it is also important to consider the impact difference between a hypothetical, decarbonised future power supply and the Severn Barrage should the Grid, for some reason remain or exceed its current carbon intensity, so these results are included for completeness.

This could be interpreted as an argument against the Barrage because commissioning such an electricity hungry technology would tie the Grid to maintaining power generation, for power generation's sake, whether it is decarbonised or not. However the consequences of the future Grid falling short of the target carbon reduction are far further reaching than the carbon performance of Severn Barrage as the need to 'keep the lights on' *already* ties the Grid to continued generation. However, the pay off for running the Barrage is, in fact, that it is able to generate lower carbon intense power than the Grid in all circumstances, and hence will *always* lower the overall National Grid carbon intensity. No such payoff is available for just 'keeping the lights on'. Perhaps most importantly, however, no matter which Severn Barrage model is considered, the savings available against the 1990 baseline Grid exceed 90%, reaching 98% in the 'best' case. This suggests that the Barrage could make a substantial contribution to reaching the UK carbon reduction target of 80% below the 1990 baseline emissions.

	Severn Barrage - 'initial' case (kg.CO_2eq/MWh(e))	**Error range - 'Worst' to 'Best' cases (kg.CO_2eq/MWh(e))**
UK National Grid 1990, baseline	754	730 - 799
UK National Grid 2008	502	478 - 547
UK 2050 – Central Control V1.1	29	5 - 74
UK 2050 – Market Rules V1.1	53	29 - 99
UK 2050 – Thousand Flowers V1.1	38	14 - 83

Table 22 Set of GWP savings per MWh(e) against National Grid mix models (to the nearest kg)

5.6.2.1 Displaced Carbon Payback Period

Table 23 shows the range of displaced carbon payback periods of the Severn Barrage against the five representations of the UK National Grid Mix. The very small savings available against the three potential 2050 Grid mixes means that the displaced carbon payback periods for the 'worst' and 'initial' cases for the Severn Barrage do extend beyond the design life of 120 years. However, as already discussed, it is most realistic to only calculate the displaced payback periods assuming that the power generated by the Severn Barrage displaces the same Grid mix that supplies it, so the real range is 22 to 14 years which is, again, less than a quarter of the full design life span.

	Displaced payback period for the Severn Barrage - 'Initial' case	**Error range - 'Worst' to 'Best' cases**
UK National Grid 1990, baseline	9	14 - 2
UK National Grid 2008	14	21 - 3
UK 2050 – Central Control V1.1	248	2110 - 22
UK 2050 – Market Rules V1.1	134	347 - 16
UK 2050 – Thousand Flowers V1.1	189	731 - 19

Table 23 Set of displaced carbon payback period results for the Severn Barrage (to the nearest year)

5.6.2.2 Carbon Results Comparison with the existing analyses reviewed

Although the results of this carbon analysis are good compared to that of other energy generation technologies, and demonstrate that the Barrage could play an important part in the UK's low carbon, highly electrified future, they indicate a much higher carbon footprint than the results of previously studies published. Table 24 presents a comparison of the carbon analysis result from this study with the results of the existing studies reviewed for background, see section 4.7. The differences are due to the more thorough inventory developed for this study, mainly the realistic estimate for the operational stage which was underestimated in the Roberts (Roberts 1982), Spevack et al (Spevack, Jones and Hammond 2011) and DECC (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010) studies and omitted completely in the SDC (Black & Veatch 2007) and Shawater (Woollcombe-Adams, Watson and Shaw 2009) studies.

	Total Lifetime GWP ($Mt.CO_2eq$)	**Specific GWP ($kg.CO_2eq/MWh$)**	**Displace Carbon Payback Period wrt Nat Grid**
SDC (Black & Veatch 2007)	5	2.4	8.16 (months)
Shawater (Woollcombe-Adams, Watson and Shaw 2009)		<6	
Spevack et al (Spevack, Jones and Hammond 2011)	19	9.5 - 11.0	
DECC (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010, Air and Climatic Factors)	-5 - 45	0 - 23	2.6 (years)
This study, 'initial' case	120	59	14 (years)
Error range, 'worst' to 'best' cases	169 - 27	83 - 13	14 - 22 (years)

Table 24 Summary carbon results from existing analyses review

5.6.3 SPECIFIC ENERGY

The energy demand per 1MWh of power generated per energy resource category for the Severn Barrage is presented in Table 25.

Impact category	**Unit**	**Severn Barrage - 'initial' case**	**Error range - 'Worst' to 'Best' cases**
Non renewable, fossil	MJ/MWh(e)	824	1020 - 21
Non-renewable, nuclear	MJ/MWh(e)	191	265 - 2
Non-renewable, biomass	MJ/MWh(e)	0	0 - 0
Renewable, biomass	MJ/MWh(e)	3	4 - 0

Table 25 Specific energy demand by resource category for the Severn Barrage (to the nearest MJ)

Figure 46 compares the energy demand per 1MWh of the Severn Barrage, with the potential error range shown, with that of the five representations of the UK National Grid. All three estimates for the Severn Barrage are considerably less than any of the estimates for the National Grid, but the differences are even greater than in the case of overall environmental impact, for instance, the specific energy demand of the Market rules National Grid is almost nine times that of the Severn Barrage. As already discussed, the 2050 Grid scenarios are not optimized to be low energy so the specific energy demand differs the least of the indicators discussed in comparison to the current and baseline Grids, so this result is not too surprising. Again, it must be noted that the energy required to make energy does not, in fact, vary very much but the energy demand is limited to those resources that can be thought of as 'capital' energy as this is the most relevant indicator of impact. The 2050 Grid scenarios rely on a slightly higher proportion of natural energy than either the current or baseline Grid, hence the noticeable but slight reduction, (slight compared to the reduction in the case of other impact indicators). The Severn Barrage however, is specifically designed to rely on natural energy to generate energy, so its specific energy demand is, approximately, as low in comparison to the current and baseline Grids as it is when considering other impact indicators. If the contribution from natural resources were included in the specific energy demand estimates, particularly if the energy from the tide was included in the Severn Barrage estimate, then the results shown in Figure 46 would be considerably closer. However, as already discussed, a comparison of this kind would not be instructive in the context of this study.

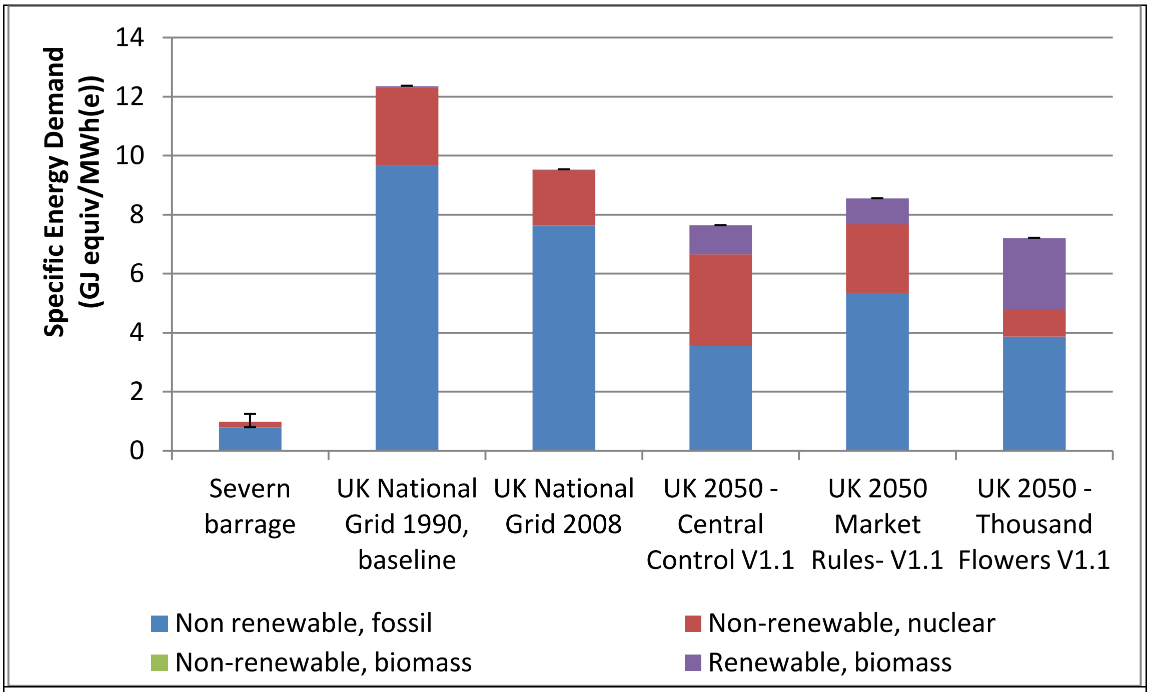

Figure 46 Comparison of specific energy demand of the Severn Barrage with that of the UK National Grid

5.6.3.1 Displaced Energy Payback Period

Table 26 shows the range of displaced energy payback periods of the Severn Barrage against the five representations of the UK National Grid Mix. The large differences in specific energy demand, shown in Figure 46, mean that in all cases the displaced energy payback period less than a year. Hence the time periods are shown in days rather than years. Again, it is useful to identify those displaced payback periods that are most realistic. The real range is only 42 to 41 days which is extremely short and provides the most striking demonstration of the minimal energy demand required by a tidal barrage of the scale of the Severn barrage to generate energy.

	Displaced payback period for the Severn Barrage - 'Initial' case (days)	Error range - 'Worst' to 'Best' cases (days)
UK National Grid 1990, baseline	31	41 - 25
UK National Grid 2008	42	55 - 33
UK 2050 – Central Control V1.1	54	71- 42
UK 2050 – Market Rules V1.1	47	63 - 37
UK 2050 – Thousand Flowers V1.1	46	61 - 37

Table 26 Set of displaced energy payback period results for the Severn Barrage (to the nearest day)

5.7 SUMMARY

The assessment has shown that the environmental impact of the Severn Barrage is small in comparison to the National Grid mix, whether a range of environmental impacts are considered or a single impact such as energy demand or carbon emission. It has also shown that the Severn Barrage can make a substantial contribution to meeting the UK carbon reduction target of 80% below 1990 levels by 2050. The carbon savings available against the 1990 baseline National Grid are in the order of 90%, with the maximum potential estimated at 98%.

The study has critiqued and streamlined the data available from existing literature in order to compile the basis of a life cycle inventory, and then carried out further and more thorough inventory analysis where required. This has resulted in a more extensive and realistic inventory than exists in any study so far published and, hence, some different results. Significantly, the assessment has shown that the operation stage of the Severn Barrage is the largest contributor to the total environmental impact of the plant over its lifetime. This finding is in stark contrast to the conclusions of the SDC (Black & Veatch 2007) and Shawater (Woollcombe-Adams, Watson and Shaw 2009) studies which both dismissed the operation stage has having minimal impact without any detailed assessment. The Roberts (Roberts 1982) and Spevack (Spevack, Jones and Hammond 2011) studies, the latter being largely based on methods from the former, did both show that the operation stage was the largest contributor to the overall impact but not to the magnitude calculated in this study. The large difference can be entirely attributed to the more realistic approach adopted for the operation stage inventory i.e. that the Roberts and Spevack analyses are based on financial estimates and this study has re-estimated the electricity requirement based on demand figures taken from the STPG report (Severn Tidal Power Group and the Department of Energy 1989). The SEA carried out as part of the DECC feasibility study claims to include the operational electricity demand but uses non-life cycle estimates for the impact intensity of the electricity supply and includes an estimate for the impact reduction service that could be provided by the additional sedimentary deposits in the estuary (Parsons Brinckerhoff Ltd; Black and Veatch Ltd; 2010), hence the impact estimate made for the operation should also be considered an underestimate. The inventory in this study uses only life cycle data and examines a range of possibilities in most cases. Hence the results found in this study are more thorough and therefore more realistic than any others published so far.

Table 27 presents the carbon and energy key findings of the life cycle assessment case study. The EGR does not compare well with other examples of renewable energy systems, however it is greater than 1 showing that energy generation will outstrip demand which is considerably better than conventional, fossil fuelled systems for which the EGR is always less than 1. Similarly, the specific carbon intensity estimates are higher than other renewables except in the best case but are much lower than conventional power system and than any of the National Grid mixes modelled by the Transition Pathways work and considerable savings are available. Both the simple energy and displaced carbon payback periods are significantly shorter than the plants design lifetime.

ENERGY ANALYSIS MAIN RESULTS			
	Life time energy demand (PJ)	Energy Gain Ratio	Energy Payback period (yrs)
Severn Barrage	19 952	3.6	33
Potential error range	25 486 - 16 208	2.8 - 4.5	42 - 27
CARBON ANALYSIS MAIN RESULT			
	Life time carbon emissions ($Mt.CO_2eq$)	Specific carbon emissions ($kg.CO_2eq/MWh$))	Displaced Carbon Payback Period (years)
Severn Barrage	120	59	14
Potential error range	169 - 27	83 - 13	14-22

CARBON SAVINGS COMPARED TO NATIONAL GRID		
	Severn Barrage, compared with the (approximate) Grid mix that supplies the Barrage ($kg.CO_2eq/MWh(e)$)	**Potential error range ($kg.CO_2eq/MWh(e)$)**
UK National Grid 1990, baseline	730	730 - 799
UK National Grid 2008	502	478 - 547
UK 2050 – Central Control V1.1	74	5 - 74
UK 2050 – Market Rules V1.1	99	29 - 99
UK 2050 – Thousand Flowers V1.1	83	14 - 83

Table 27 Case study: Severn Barrage - summary table of main findings

The study findings demonstrate that the impact of the plant is most sensitive to improvements in the operation stage of its life. The largest improvement to the impact of the operation stage can be made by removing the electricity demand for 'flood pumping', although this will reduce the plant's generating capacity. This option is investigated in Chapter 6. If, however, this large modification in operating method is not adopted, improvements in the operation stage can only be made via improvements in the National Grid Mix, especially with respect to carbon reductions. So, rather satisfyingly, bar operational mode alterations, the most effective approach to improve the Severn Barrage design would be to reduce the environmental impact, particularly the carbon intensity, of the National Grid. The most appropriate steps to achieve this would be to identify and assess potential low impact technologies which can contribute to the future National Grid mix, which is, in fact, the original research proposal as well as the prime directive of the UK 'sustainable energy' movement, including the Transition Pathways Consortium.

CHAPTER 6. SEVERN BARRAGE IMPROVEMENT ANALYSIS: EXCLUDE ‘FLOOD PUMPING’

6.1 IN THIS CHAPTER

The Barrage was re-assessed within the assumption that the plant would operate without ‘flood pumping’; which is the act of reversing the turbines to pump water from the seaward side to the basin at each high tide in order to maximize the head deferential before generation begins.

6.2 ADDITIONAL INVENTORY ANALYSIS

The LCA case study of the Severn Barrage showed that by far the largest contribution to the overall impact, in all impact indicators investigated, was accountable to the operation stage of the Barrage and that, therefore, this is the area where the greatest improvements can be made.

The impact of the operation stage is mainly accountable to the electricity bought from the Grid to drive the ‘flood pumping’ operation. However, it is not a certainty that the ‘flood pumping’ would be included in the Barrage operational regime. Hydraulic modelling (0-D) completed by the STPG in 1989 found that ‘flood pumping’ could lead to a 9.7% increase in energy output over ebb generation only and therefore concluded that ‘flood pumping’ was required (Severn Tidal Power Group and the Department of Energy 1989). More recent modelling carried out for the SDC study estimated that gains from ‘flood pumping’ could be 10.3% when repeating the STPG modelling method (0-D), however, when more sophisticated techniques (1-D and 2-D) were applied gains were estimated to be as low as 3.2% and 2.7% (Black & Veatch 2007). To the nearest TWh, however, it can be assumed that the average annual output in ebb generation only mode would be 16 TWh, giving a lifetime output figure of 1920 TWh, which means that, over its lifetime, 175 TWh of power input from the Grid to drive ‘flood pumping’ leads to only 120 TWh of power output from the Barrage. This simple calculation alone implies that ebb generation mode only would be the optimal operational strategy. A revised inventory was prepared that excluded the power requirement for ‘flood pumping’, reducing the annual operational electricity demand to 20TWh, which is still required for ancillary processes. Further impact analysis was carried out using this inventory to assess the effect of changing the Barrage operational mode.

6.3 LIFE CYCLE ASSESSMENT RESULTS INTERPRETATION

Table 28 shows the characterised impact results for the lifetime environmental impact of the Severn Barrage on the assumption that it operates in ebb generation mode only and the savings that are available over operating in ebb generation with ‘flood pumping’, and the potential error range. Impact savings are available in every impact category and are 50% or more of the impact for the originally analysed system, i.e. ebb generation with ‘flood pumping’, in most instances, and are over 80% in 7 out of 18 categories. It is only the category of metal depletion that sees a saving of much less than 50%; only a 3% saving is available in this category because the operation stage was already the smallest contributor, the largest being the maintenance stage which makes up 62% and 64% of the lifetime metal demand, with and without pumping respectively.

Impact category	Unit	Severn Barrage, exclusive of 'flood pumping'	*Saving/cost over system inclusive of 'flood pumping'*	Error Range - 'Worst' to 'Best' case exclusive of 'flood pumping'	*Saving/cost error range*
Climate change	$t.CO_2eq$	21 257 500.0	*98 255 700.0*	26 287 700.0 - 11 419 400.0	*142 397 000.0* *- 15 335 560.0*
Ozone depletion	t.CFC-11-eq	1.1	*2.6*	1.2 - 1.0	*3.5* *- 2.3*
Human toxicity	t.1,4-DB-eq	6 500 500.0	*20 843 60. 0*	8 810 834.1 - 5 737 710.5	*40 690 800.0* *- 14 496 200.0*
Photochemical oxidant formation	t.NMVOC	60 442.9	*212 141.0*	81 668.6 - 46 509.9	*390 858.0* *- 112 284.0*
Particulate matter formation	t.PM10-eq	45 105.9	*101 086.0*	262 000.0 - 39 316.6	*217 830.0* *- 55 930.4*
Ionising radiation	t.U235-eq	5 147 280.0	*31 728 600.0*	6 706 200.0 - 7 490 210.0	*44 615 000.0* *- 52 600 500.0*
Terrestrial acidification	$t.SO_2$-eq	77 532.8	*328 771.0*	129 647.0 - 55 574.6	*757 757.0* *- 148 322.0*
Freshwater eutrophication	t.P-eq	6 255.8	*29 073.5*	9 687.1 - 4 482.5	*58 365.0* *- 13 754.0*
Marine eutrophication	t.N-eq	3 477.6	*14 711.8*	5 018.7 - 2 534.3	*27 773.7* *- 7 229.9*
Terrestrial ecotoxicity	t.1,4-DB-eq	1 357.0	*1 710.4*	1 670.9 - 4 146.2	*4 671.9* *- 26 520.0*
Freshwater ecotoxicity	t.1,4-DB-eq	461 044.0	*447 435.0*	512 145.0 - 435 802.0	*886 699.0* *- 232 596.0*
Marine ecotoxicity	t.1,4-DB-eq	482 465.0	*475 503.0*	531 911.0 - 455 936.0	*896 448.0* *- 250 006.0*
Agricultural land occupation	km^2	312.9	*1 341.9*	473.2 - 593.6	*2 741.9* *- 3 819.1*
Urban land occupation	m^2	162 266 000	*439 433 000*	408 721 000 - 139 326 000	*846 917 000 -* *262 936 000*
Natural land transformation	km^2	6.8	*20.6*	19.7 - 4.0	*1.9* *- 8.5*
Water depletion	km^3	0.2	*0.5*	0.2 - 0.2	*0.6* *- 0.4*
Metal depletion	t.Fe-eq	16 545 100.0	*486 085.0*	16 553 900.0 - 16 612 600.0	*653 417.0* *- 1 197 980.0*
Fossil depletion	t.oil-eq	6 440 900.0	*31 849 000.0*	7 411 780.0 - 4 379 860.0	*40 413 400.0* *- 14 766 800.0*

Table 28 Characterised results by impact category of the Severn Barrage when 'flood pumping' is excluded and the impact savings available in comparison to including 'flood pumping', using Midpoint (H European) Analysis (to 1 decimal place)

The total normalized impact score of the Severn Barrage when it is assumed to operate in ebb generation mode represents a saving of 65% in the 'initial' case over the original system, i.e. ebb generation with 'flood pumping'. The worst case estimate is actually less than the best case under the original operating assumptions. The overall impact results for both the 'best' case models, with and without 'flood pumping', have a lower proportional contribution from the operation stage, but even when these are compared, the savings available reach 53%. The total value of the normalized impact score of the Barrage in ebb generation mode only is 205 million which in a range of 326-174 million. That gives a score of 2 million in a range of 3 – 1 million per year of life. This means that without flood pumping, the reduced emission rate of the Barrage scheme is approximately equivalent to 2 million average European citizens, which is roughly the population Hamburg.

Figure 47 compares the overall environmental impact of the Severn Barrage when operating in ebb generation with 'flood pumping' for its full lifetime to that of the Severn Barrage when ebb generation only is adopted for operation, along with a possible range of error for each. The reduction in impact and in error range can be seen clearly. Importantly the maximum impact estimate for the Severn Barrage when it is assumed that 'flood pumping' is not adopted is less than the minimum impact estimate when it is assumed that it is, indicating that the excluding 'flood pumping' will always yield a better environmental impact score, irrespective of what other decisions are made.

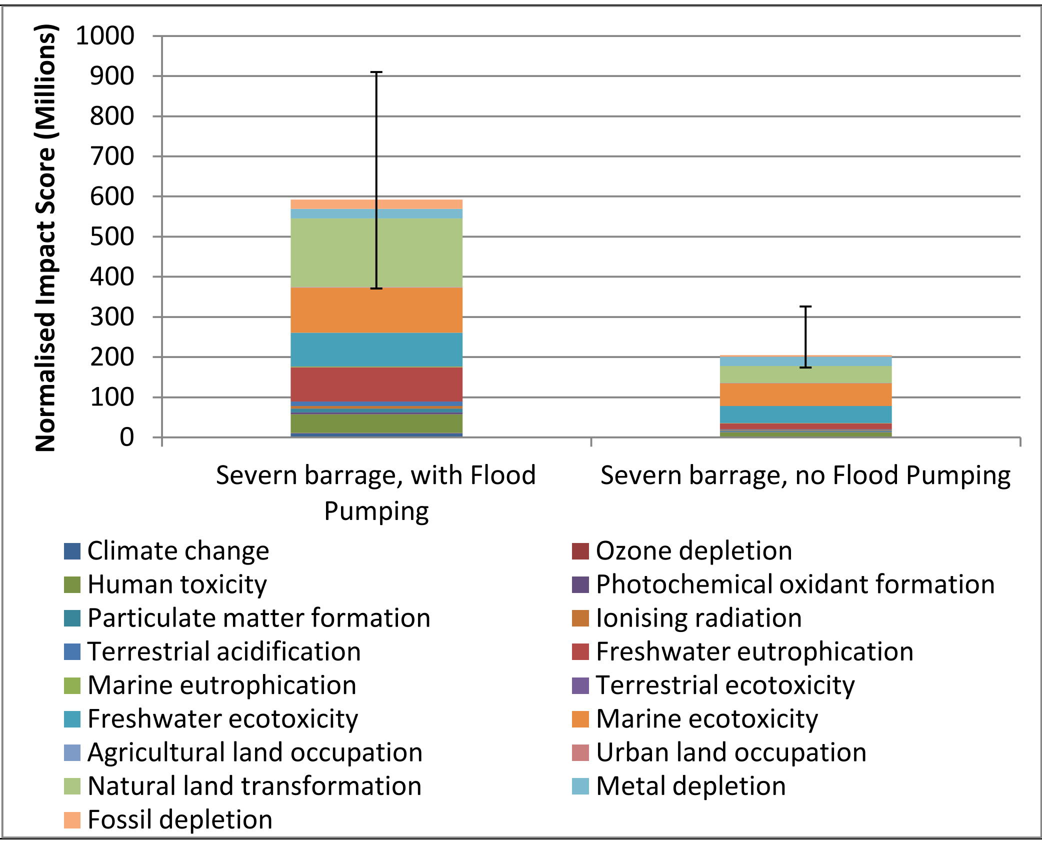

Figure 47 Comparison of the total normalised scores for the Severn Barrage, with and without 'flood pumping'

Figure 48 shows the normalized impact scores for Severn Barrage when it is assumed the plant operates in ebb generation mode only for each impact category, with the contribution from each life stage shown and a possible range of error. When this figure is compared to Figure 36, the effect of removing the electricity demand can be seen. The normalized impact score in all categories has reduced, in line with the characterised results, and, as would be expected, this is due to the significantly reduced contribution from the operational stage, which was dominant in ever impact category. It can be seen that the categories where the contribution from the operational stage was large and the contribution from the other two modelled life stages was small, such as freshwater eutrophication, human toxicity and fossil fuel depletion, now make a much smaller contribution to the overall lifetime impact score. Categories where the life stages of construction and maintenance make a greater contribution are now the more dominant impacts, such as marine and freshwater ecotoxity, natural land transformation and metal depletion.

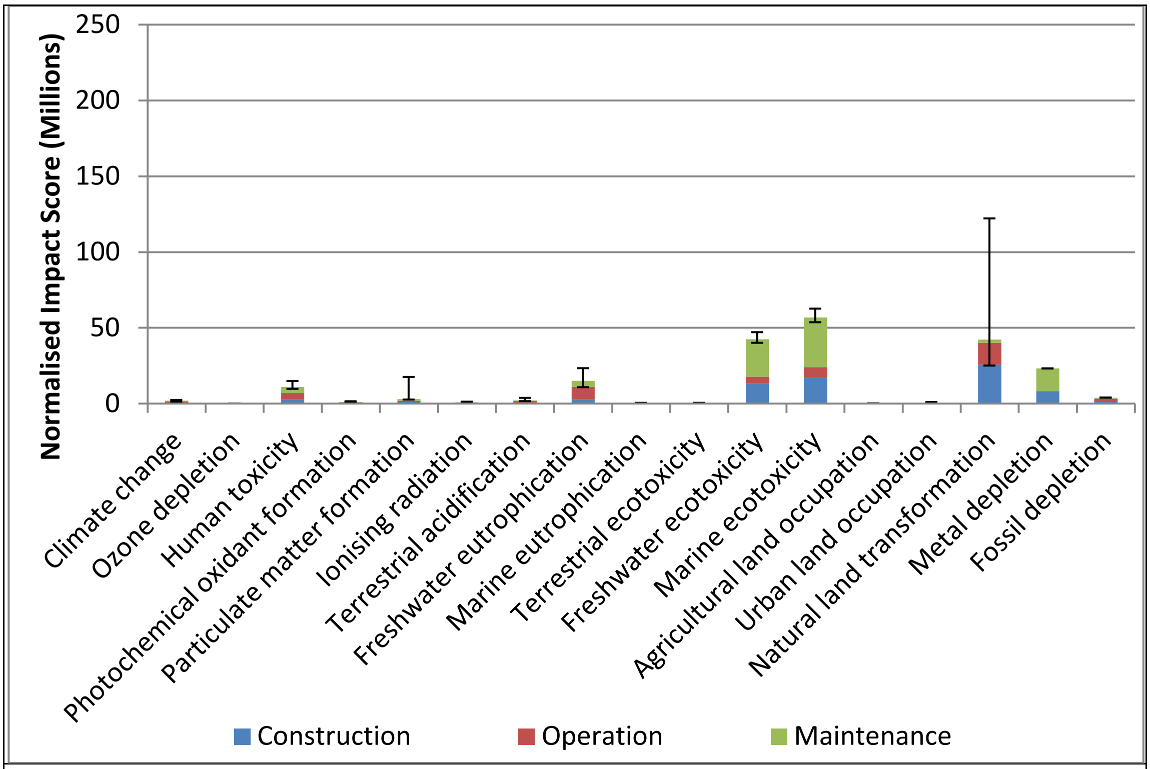

Figure 48 Normalised results by impact category for each of the modelled life stages of the Severn Barrage without 'flood pumping', including the possible range of scores, using Midpoint (H European) Analysis

Figure 49 shows the same results as Figure 48 but with the axis reversed so that the impact of the three modelled life stages can be more easily compared. It can be seen that despite the long operational life of the Barrage, the impact of the operation stage could be reduced so that it is the least impactful stage in almost all scenarios. The 'worst' case operation impact score is approximately equal to the 'best' case construction score, but this is the only instance where the separate life stages come close. In the 'worst' case the construction stage is now estimated to be the dominant contributor to overall life impact, but in all other scenarios the maintenance stage dominates. Figure 49 also shows that the magnitude of the impact error range is now dominated by that of the range estimated at the construction stage. This indicates, if the plant operates without 'flood pumping', the next greatest impact reductions depend on the decisions made at the construction stage.

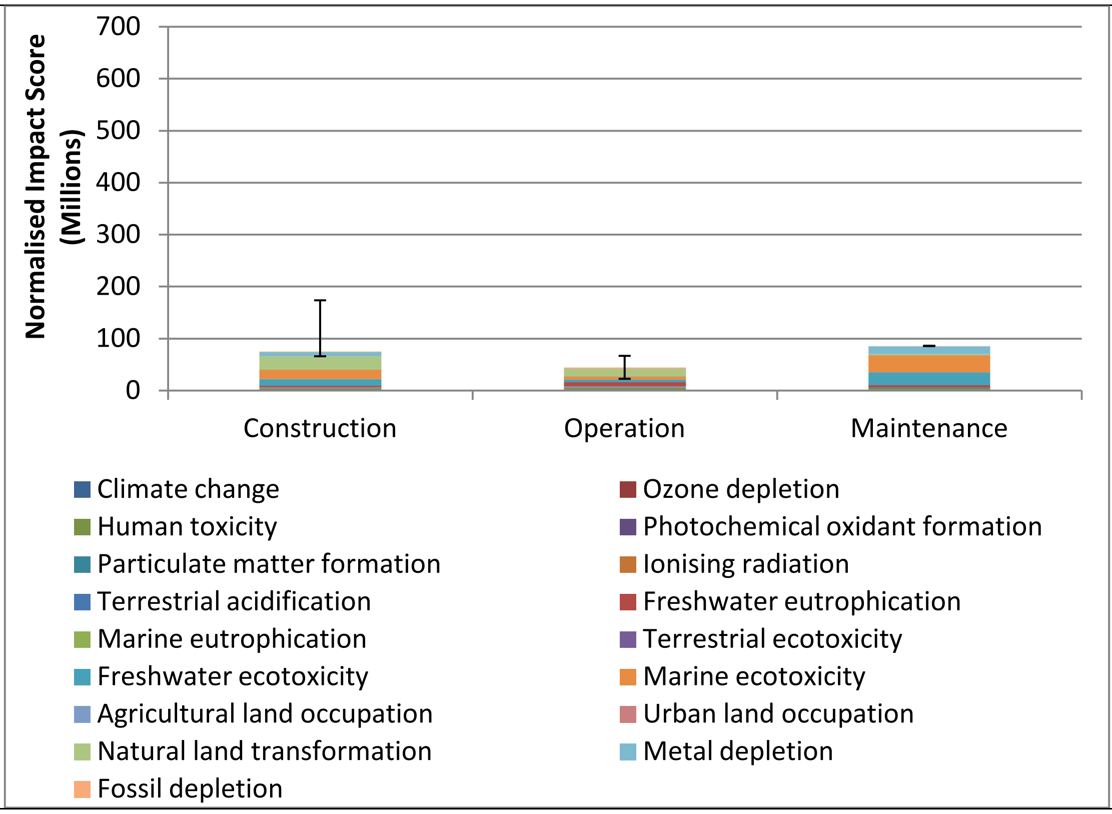

Figure 49 Normalised scores per life stage for the Severn Barrage without 'flood pumping', including the possible range of scores

6.3.1 CARBON ANALYSIS

As can been seen in Table 28, the total lifetime GWP for the Severn Barrage, in ebb generation only mode, is estimated at 21 Mt.CO_2 (equivalent), with a range of 26 to 11 Mt.CO_2 (equivalent). This represents a saving of 82% over ebb generation with 'flood pumping', in a range of 84% to 57%, comparing 'worst' and 'best' case inventories respectively. In every scenario, this is a significant saving. Importantly, the 'worst' case GWP estimate without 'flood pumping' is slightly less than the 'best' case GWP estimate with 'flood pumping', indicating that excluding 'flood pumping' will always provide a lower impact system than if it were included, as was the case for the overall normalized impact score.

Figure 50 compares the GWP estimates for the three modelled life stages of the Barrage, under the assumption that no 'flood pumping' is employed. When Figure 50 is compared to Figure 41 in section 5.5.1, the GWP reduction at the operational stage can be seen clearly. When the plant operates in ebb generation mode only, the estimated operational GWP is 11 Mt.CO_2 (equivalent) which represents an almost 10 fold reduction, with a range of 16 Mt.CO_2 (equivalent) to 2 Mt.CO_2 (equivalent). However, in contrast to the overall environmental impact, it can also be seen that the impact at the operation stage is still dominant in all but the 'best' case. Also, Figure 50 shows that the range in error for overall GWP is still almost entirely due to that of the estimates at the operation stage. These results demonstrate the dominant effect that the carbon intensity of the National Grid itself has on the overall carbon intensity of the plant, even when the operational power demand is drastically reduced.

These results also further highlight the significance of the error that previous carbon analyses have made in under estimating (Roberts 1982) (Spevack, Jones and Hammond 2011) or neglecting (Black & Veatch 2007) (Woollcombe-Adams, Watson and Shaw 2009) the operational impact.

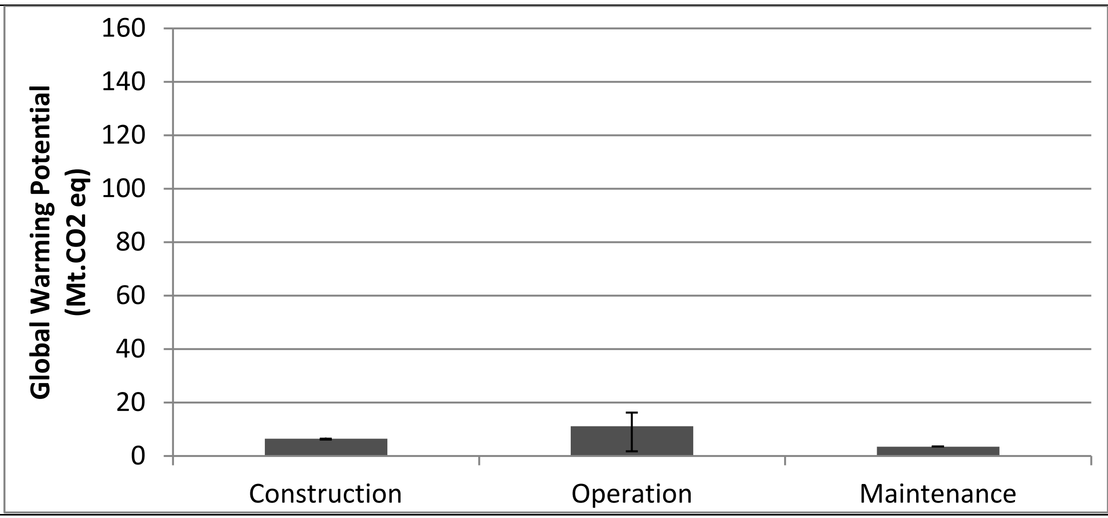

Figure 50 GWP (expressed in Mt.CO_2eq) by life stage for the Severn Barrage without 'flood pumping', including the possible range of scores

6.3.2 ENERGY ANALYSIS

Removing the energy required for 'flood pumping' has reduced the overall plant energy demand to 324,808 TJ, with a range of 382,066 – 281,871 TJ. Table 29 shows the lifetime energy demand of the Severn Barrage on the assumption that it operates in ebb generation mode only and the savings that are available over operating in ebb generation with 'flood pumping'. Again, the energy from the natural resource categories of renewable wind, solar, geothermal and renewable water are given in the table for completeness but are excluded from any analysis or total energy demand figures quoted.

Impact category	Unit	Severn Barrage, exclusive of 'flood pumping'	*Saving/cost over 'flood pumping' operation*	Error Range - 'Worst' to 'Best' case exclusive of 'flood pumping'	*Saving/cost error range*
Non renewable, fossil	TJ	270 478	1 337 284	311 231 - 183 933	1 696 767 - 620 027
Non-renewable, nuclear	TJ	53 015	329 198	69 133 - 77 414	462 715 - 546 421
Non-renewable, biomass	TJ	0	1	0	0
Renewable, biomass	TJ	1 315	3 874	1 703 - 20 524	7 065 - 172 463
Renewable, wind, solar, geothermal	*TJ*	*1 734*	*13 206*	*299 - 23 930*	*480 - 207 928*
Renewable, water	*TJ*	*13 916*	*11 116*	*14 574 - 18 516*	*14 958 - 52 136*

Table 29 Lifetime energy demand per energy resource category by life stage for each impact category for the bio-gas fuelled CHP (to the nearest GJ)

Figure 51 shows the energy demand for the Severn Barrage scheme across the life stages of construction, operation and maintenance, under the assumption that no 'flood pumping' is employed in operation. Energy demand at the operation stage has reduced by approximately a factor of 10, in line with the magnitude of the GWP reduction, to 190,421 TJ. Also in line with the GWP result, the operation stage is still the most energy intense stage, despite the large reduction in demand. Furthermore, the energy demand of 'best' case operation is still greater than the 'worst' case for either of the other modelled life stages. These results show the dominant effect that the operational power demand has on the lifetime energy demand. Improvements to the remaining plant operations to reduce power demand will still have a far greater effect on the overall demand than design choices made in the construction or maintenance stages, no matter what the energy profile of the Grid.

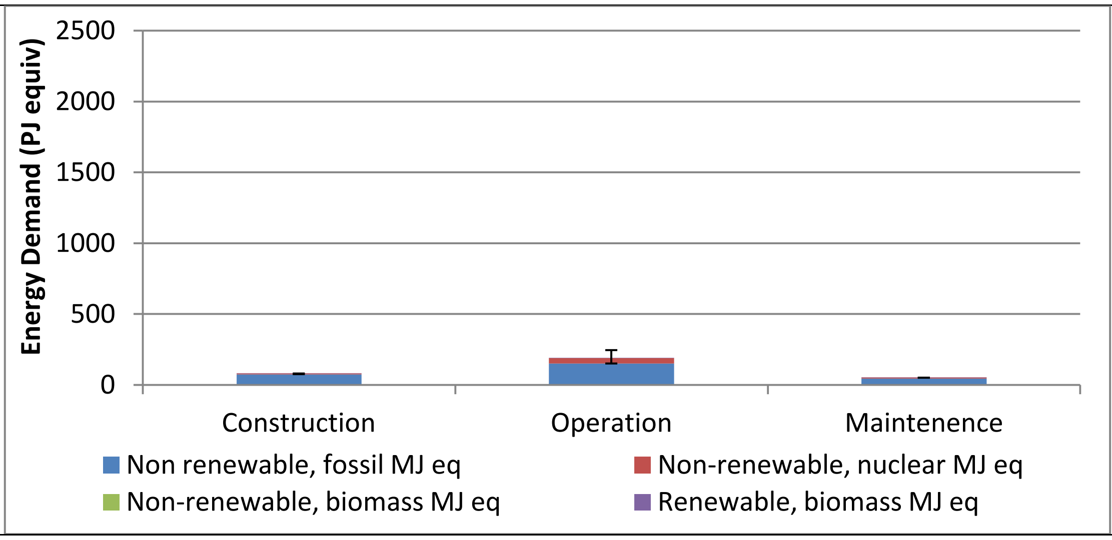

Figure 51 Energy demand of the Severn Barrage without 'flood pumping' by life stage, including the possible range of scores

The energy gain ratio for the plant assuming ebb generation only is calculated at 21.5, with a range of 18.3 to 37.8. These figures are now comfortably comparable with estimates for wind power (Lenzen and Munksgaard 2001) and better than those calculated for other marine power systems (Parker, Harrison and Chick 2007) (Douglas, Harrison and Chick 2007), as well as significantly bettering typical EGRs for conventional power systems. The energy payback period is 6 years, with a range of 7 to 5 years. That is an increased energy gain of around 6 times and payback is achieved around 6 sooner than when 'flood pumping' is employed. Even though the removal of the 'flood pumping' mode would reduce the power capacity of the plant, the huge reduction in power demand is sufficient to yield these much improved figures. These results support the case that, from an energy optimisation point of view, 'flood pumping' should not be employed.

The operational energy demand is now only 10% different from the Spevack estimate (Spevack, Jones and Hammond 2011), and the EGR and payback periods are comparable. However, as already discussed in Chapter 5, the annual power output used in the Spevack analysis necessarily implies that it is based on a plant that employs 'flood pumping', and hence these results generated on the assumption that 'flood pumping' is not employed should not, therefore, be comparable.

6.4 LIFE CYCLE ASSESSMENT RESULTS INTERPRETATION: POWER IN CONTEXT

As already stated, it was assumed that operating the Severn Barrage in ebb generation mode only would reduce its average annual output to 16 TWh and, hence, its lifetime power output to 1920 TWh. The total lifetime impact results given in Table 28 where divided by this lifetime power output to give the impact per 1MWh of power generated. Table 30 presents the resultant specific characterised impact results per impact category. As was the case for the overall lifetime results, the removal of 'flood pumping' offers significant savings over the originally modelled operational mode.

Impact category	**Unit**	**Severn Barrage, exclusive of 'flood pumping'**	**Error Range - 'Worst' to 'Best' case exclusive of 'flood pumping'**
Climate change	kg.CO_2eq/MWh(e)	11	14 - 6
Ozone depletion	kg.CFC-11-eq/MWh(e)	0	0 - 0
Human toxicity	kg.1,4-DB-eq/MWh(e)	3	5 - 3
Photochemical oxidant formation	kg.NMVOC/MWh(e)	0	0 - 0
Particulate matter formation	kg.PM10-eq/MWh(e)	0	0 - 0
Ionising radiation	kg.U235-eq/MWh(e)	3	3 - 4
Terrestrial acidification	kg.SO_2-eq/MWh(e)	0	0 - 0
Freshwater eutrophication	kg.P-eq/MWh(e)	0	0 - 0
Marine eutrophication	kg.N-eq/MWh(e)	0	0 - 0
Terrestrial ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0 - 0
Freshwater ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0 - 0
Marine ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0 - 0
Agricultural land occupation	m^2/MWh(e)	0	0 - 0
Urban land occupation	m^2/MWh(e)	0	0 - 0
Natural land transformation	m^2/MWh(e)	0	0 - 0
Water depletion	m^3/MWh(e)	0	0 - 0
Metal depletion	kg.Fe-eq/MWh(e)	9	9 - 9
Fossil depletion	kg.oil-eq/MWh(e)	3	4 - 2

Table 30 Specific characterised results by impact category for the power generated by the bio gas fuelled CHP, using Midpoint (H European) Analysis (to the nearest whole unit)

Figure 52 compares the specific normalized impact score of the Severn Barrage, assuming ebb generation only, with that of the five representations of the UK National Grid (Hammond, Howard and Jones 2013). The results presented in section 5.6 showed that the Barrage could offer significant impact savings even when 'flood pumping' was employed, so it is not surprising that the removal of 'flood pumping' just increases the magnitude of the savings available.

A further interesting observation can be made at this stage. When the operational impact is dominant, in the case of ebb generation with 'flood pumping', increasing the operational lifetime of the plant would not improve the specific impact as the overall impact would increase, approximately, proportionally to the power output; however, if the 'one off' activity of construction is the dominant contributor, as was proposed would be the case in the 'worst' case scenario assuming ebb generation only, extending operational lifetime and hence lifetime power output would reduce specific impact and further increase the savings against the National Grid. If maintenance is the dominant contributor the effect on specific impact becomes more complicated as the maintenance regime that might be implemented after 120 years of life and its subsequent effect on power output is subject to a number of unknown, and arguably unknowable, variables.

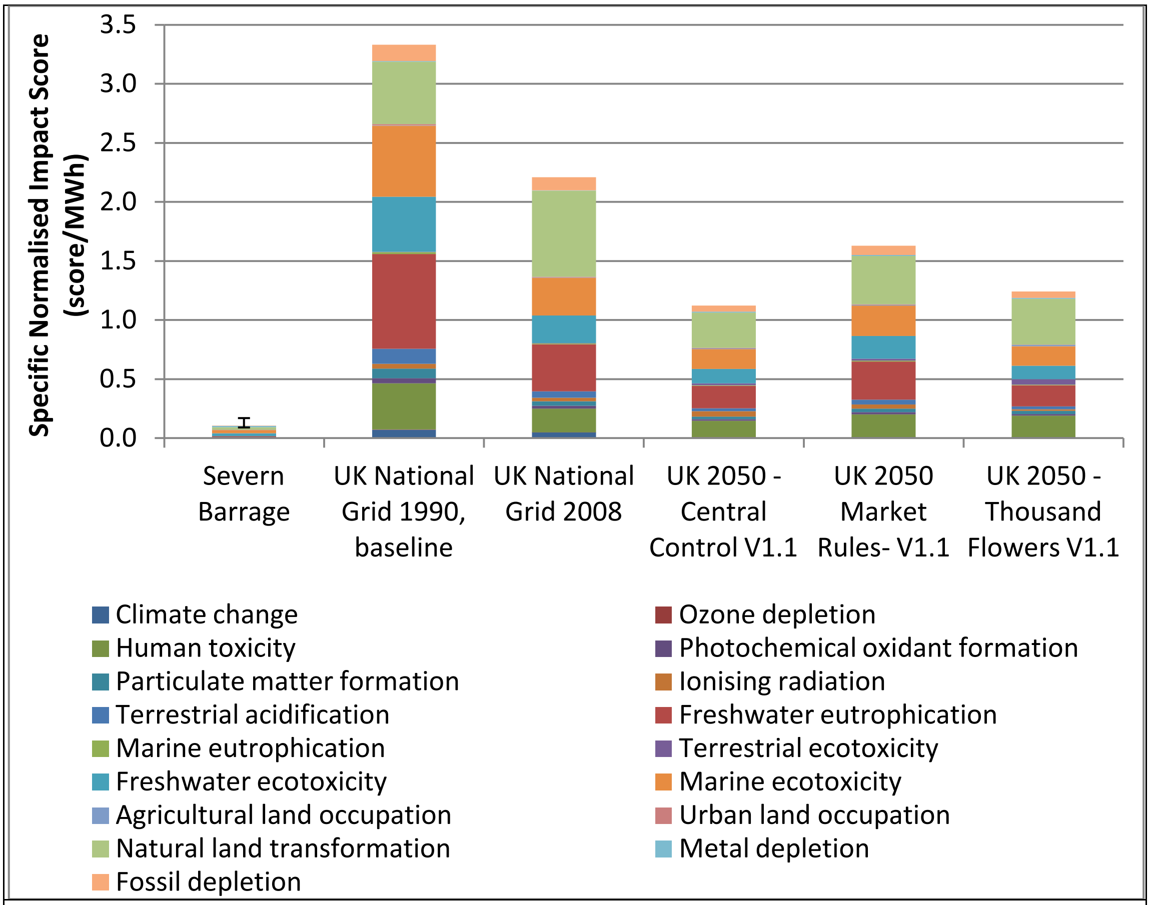

Figure 52 Comparison of specific normalised scores of the Severn Barrage without 'flood pumping' with that of the UK National Grid, using Midpoint (H European) Analysis, using Midpoint (H European) Analysis

Table 31 presents the displaced environmental paybacks for the Severn Barrage, assuming ebb generation only, against the five representations of the UK National Grid (Hammond, Howard and Jones 2013), using the total normalized impact score to represent total environmental impact. The time periods estimated are significantly reduced compared to those presented in section 5.6, which were already promising results. As stated in section 5.6, the most realistic results are given when the Severn Barrage is assumed to displace the Grid mix that supplies it, hence the range can be reduced to 6 to 3 years, which is a less than a 20th of the design lifespan.

	Displaced payback period for the Severn Barrage, exclusive of 'flood pumping'	Error Range - 'Worst' to 'Best' case exclusive of 'flood pumping'
UK National Grid 1990, baseline	4	3 - 1
UK National Grid 2008	6	5 - 2
UK 2050 – Central Control V1.1	12	14 - 4
UK 2050 – Market Rules V1.1	8	8 - 2
UK 2050 – Thousand Flowers V1.1	11	12 - 3

Table 31 Set of displaced impact payback period results for the Severn Barrage (to the nearest year)

6.4.1 SPECIFIC CARBON

The GWP per 1MWh of power generated is estimated at 11 kg.CO_2 (equivalent), with a potential error range of 14 to 6 kg.CO_2 (equivalent), see Table 30. Figure 53 shows that the specific carbon intensity of power output of the Severn Barrage is now almost negligible in comparison to that of the National Grid representations. However, as was the case in the original analysis, see Chapter 5, the relative carbon savings against the future Grid representations are much less than the normalized impact savings because of the proportion of low carbon but not low impact technologies, such as coal fired energy generation with CCS. It has been shown that the operation stage is still dominant to the overall GWP and hence to the specific GWP, so it is unlikely that expended operational life would lead to a reduction in specific GWP (as is probably the case for specific environmental impact).

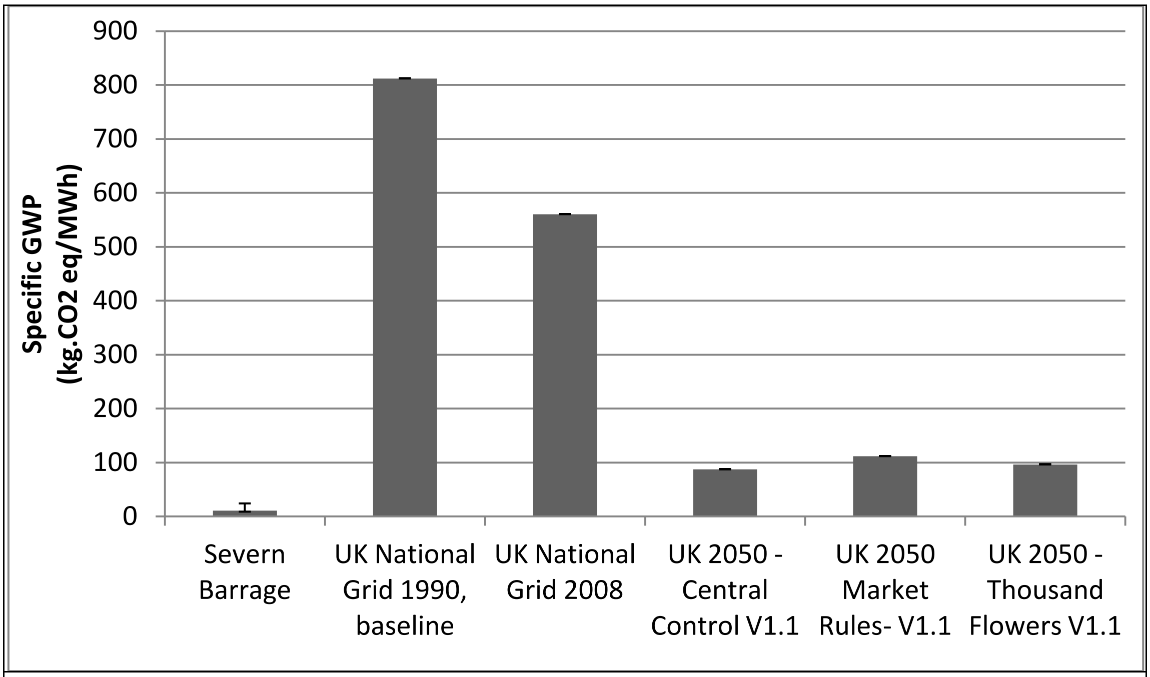

Figure 53 Comparison of specific GWP of the Severn Barrage without 'flood pumping' with that of the UK National Grid

Table 32 tabulates the carbon (equivalent) savings available per 1MWh against the five National Grid models. It can be seen that the savings available are substantial in all comparisons. The removal of 'flood pumping' negates some of the potential argument that the Severn Barrage would place an unreasonable additional demand on the National Grid as power demand is so reduced and the carbon savings available are so significant. Again the realistic range of savings can be further limited to 788 to 79 kg.CO_2 (equivalent). However, the importance of the savings against the baseline Grid should be highlighted as they range from 97% to 99% of the baseline specific carbon intensity. This further confirms the significant contribution that the Severn Barrage could make to meeting the UK carbon reduction target, especially if it operates in ebb generation only mode.

	Severn Barrage, exclusive of 'flood pumping' (kg.CO_2eq/MWh(e))	**Error range - 'Worst' to 'Best' cases (kg.CO_2eq/MWh(e))**
UK National Grid 1990, baseline	801	788 - 804
UK National Grid 2008	549	536 - 552
UK 2050 – Central Control V1.1	76	63 - 79
UK 2050 – Market Rules V1.1	101	88 - 103
UK 2050 – Thousand Flowers V1.1	85	72 - 88

Table 32 Set of GWP savings per MWh(e) against National Grid mix models (to the nearest kg)

Table 33 shows the displaced carbon payback period estimates for the Severn Barrage, ebb generation only, against the five representations of the National Grid (Hammond, Howard and Jones 2013). All estimates are now considerably less the plants design lifetime of 120 years. Again, the realistic range can be reduced to only 9 to 2 years.

	Displaced payback period for the Severn Barrage, exclusive of 'flood pumping' (years)	**Error Range - 'Worst' to 'Best' case exclusive of 'flood pumping' (years)**
UK National Grid 1990, baseline	1	2 - 1
UK National Grid 2008	2	3 - 1
UK 2050 – Central Control V1.1	17	26 - 9
UK 2050 – Market Rules V1.1	13	19 - 7
UK 2050 – Thousand Flowers V1.1	15	22 - 8

Table 33 Set of displaced carbon payback period results for the Severn Barrage (to the nearest year)

Again, the specific carbon results are now comparable with the Spevack (Spevack, Jones and Hammond 2011) result and also with the Shawater (Woollcombe-Adams, Watson and Shaw 2009) results, see Table 24. The similarity with the Shawater results must be considered no more than coincidence as the inventories vary so much, i.e. the Shawater study does not include an estimate for operational emissions. The similarity with the Spevack result may demonstrate that the method adopted from the Roberts study (Roberts 1982) is, in fact, accurate if the operational mode is assumed to be ebb generation only. However, this would mean that the subsequent energy and carbon metrics calculated in the Spevack study are inaccurate as the assumed annual power output used, necessarily assumes that 'flood pumping' *is* included. The results presented here are still significantly more than the SDC estimate.

6.4.2 SPECIFIC ENERGY

The energy demand per 1MWh of power generated per energy resource category for the Severn Barrage assuming ebb generation only is presented in Table 34. As can be seen in the table, the energy demand from nuclear and renewable biomass actually increases in the 'best' case, this is because of the increase in technologies of this types in the potential future Grid mix. The increases in these categories are, however, more than offset by the decrease in demand from fossil fuel so the overall specific energy demand in the 'best' case does still yield the lowest estimate.

Impact category	Unit	Severn Barrage, exclusive of 'flood pumping'	Error range - 'Worst' to 'Best' cases
Non renewable, fossil	MJ/MWh(e)	141	162 - 96
Non-renewable, nuclear	MJ/MWh(e)	28	36 - 40
Non-renewable, biomass	MJ/MWh(e)	0	0 - 0
Renewable, biomass	MJ/MWh(e)	1	1 - 11

Table 34 Specific energy demand by resource category for the Severn Barrage (to the nearest MJ)

Figure 54 compares the specific energy demand of power generated by the Severn Barrage when ebb generation mode only is employed. As was the case when considering specific GWP, the specific energy demand of the Severn Barrage in this case is negligible in comparison to that of all representations for the National Grid.

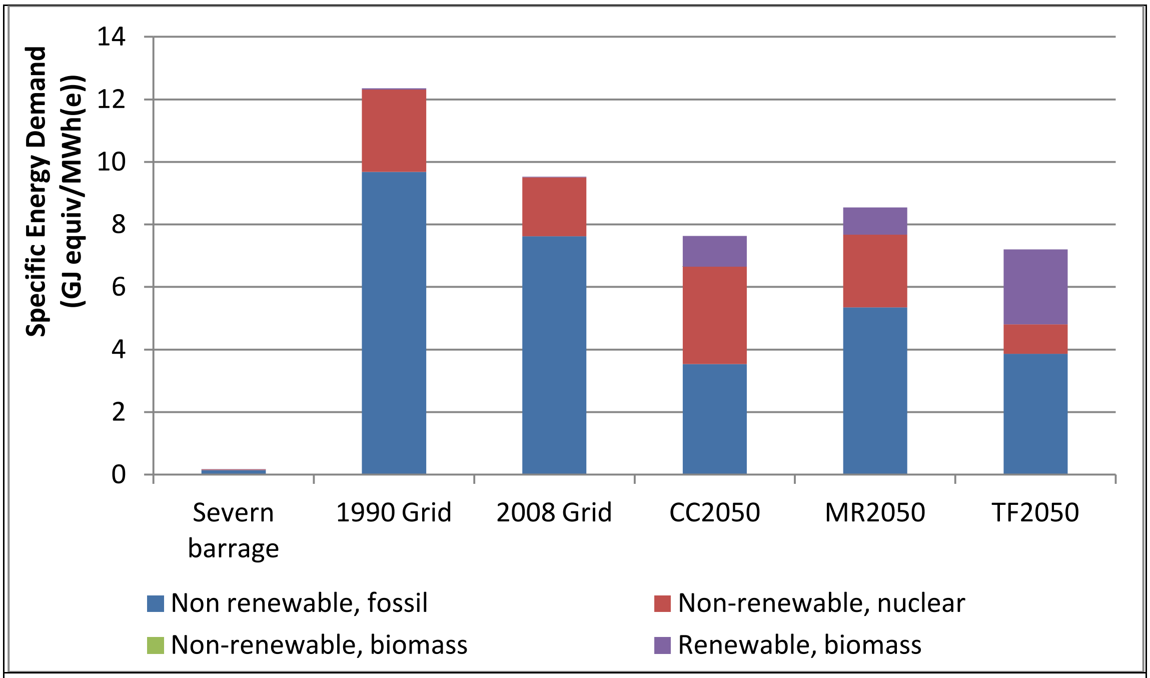

Figure 54 Comparison of specific energy demand of the Severn Barrage without 'flood pumping' with that of the UK National Grid

Table 35 shows the estimated displaced energy payback periods for the Severn Barrage, without 'flood pumping', against the five representations of the National Grid. The estimates for the Barrage inclusive of 'flood pumping' were already extremely low, see Table 26, but the values presented for the systems exclusive of 'flood pumping' are so low as to be considered nil. Even more so when it is considered that the 'realistic' range is only 6 to 7 days. This means that the energy savings that the Severn Barrage could offer against the National Grid power supply that it displaces could offset the whole life time energy demand of the scheme in less than a week from when it begins operating at full capacity, if 'flood pumping' is not employed.

	Displaced payback period for the Severn Barrage, exclusive of 'flood pumping' (days)	Error Range - 'Worst' to 'Best' case exclusive of 'flood pumping' (days)
UK National Grid 1990, baseline	5	6 - 4
UK National Grid 2008	7	8 - 6
UK 2050 – Central Control V1.1	8	10 - 7
UK 2050 – Market Rules V1.1	7	9 - 6
UK 2050 – Thousand Flowers V1.1	9	10 - 8

Table 35 Set of displaced energy payback period results for the Severn Barrage (to the nearest day)

6.5 SUMMARY

The original LCA case study showed that the most impactful life stage of the Severn Barrage was by far the operation stage and this was entirely due to the large electricity demand over the plants 120 year lifespan, which was in turn largely due to the power demand to power required to drive the turbines as pumps in order to achieve ebb generation with 'flood pumping'. In order to investigate the effect of removing 'flood pumping' from the operational mode, the impact assessments were reapplied to an inventory that excluded 'flood pumping'. Although the switch to operating in ebb generation mode only will lead to a slight reduction in net power output, the analysis has shown that, from a simple energy investment point of view as well as from a life cycle impact point of view, irrespective of the impact indicator considered, the disadvantages of removing 'flood pumping' are far out weighted by the advantages, and that ebb generation only should be the adopted operational regime.

Table 36 presents the carbon and energy key findings of the life cycle assessment improvement analysis for the Severn Barrage life cycle assessment case study. The energy gain ratio for the system has increased and now shows an energy performance that is comparable to, or an improvement on, other renewable energy systems. The simple energy and displaced carbon paybacks have decreased significantly compared to the original case study, the latter being now a matter of days rather than years. Importantly the carbon savings now available against the 1990 baseline National Grid have been shown to reach at least 97%, potentially reaching 99%, which demonstrate the hugely significant opportunity that the Barrage could offer with regard to achieving the National carbon reduction target.

ENERGY ANALYSIS MAIN RESULTS			
	Life time energy demand (PJ)	Energy Gain Ratio	Energy Payback period (yrs)
Severn Barrage, ebb generation only	325	21.5	6
Potential error range	382 - 282	18.3 – 37.8	7 - 5

CARBON ANALYSIS MAIN RESULT			
	Life time carbon emissions (Mt.CO_2eq)	Specific carbon emissions (kg.CO_2eq/MWh))	Displaced Carbon Payback Period (days)
Severn Barrage, ebb generation only	21	11	7
Potential error range	26 - 11	14 - 6	5-7

CARBON SAVINGS COMPARED TO NATIONAL GRID		
	Severn Barrage, compared with the (approximate) Grid mix that supplies the Barrage (kg.CO_2eq/MWh(e))	**Potential error range (kg.CO_2eq/MWh(e))**
UK National Grid 1990, baseline	804	788 – 804
UK National Grid 2008	549	536 – 552
UK 2050 – Central Control V1.1	79	63 -79
UK 2050 – Market Rules V1.1	103	88 – 103
UK 2050 – Thousand Flowers V1.1	88	72 - 88

Table 36 Case study improvement analysis: Severn Barrage - summary table of main findings

The analysis has shown that in terms of environmental impact (represented by total normalized impact score), removing the power demand for ‘flood pumping’ reduces the contribution of the operation stage so much that it becomes less impactful than the maintenance stage in all cases (i.e. under ‘worst’ to ‘best’ assumptions) and less impactful than the construction stage in all but the ‘best’ case. Furthermore, the magnitude of the error range is now mostly associated with the decisions made at the construction stage. This suggests that if ebb generation only mode was adopted, as has been shown to be optimal, the greatest opportunities for further environmental impact reduction are available at the construction stage. If the ‘one off’ activity of construction is the dominant contributor, then further reductions in specific impact, and hence increased savings against the Grid, could be achieved by extending the plant life lifetime.

However, when considering GWP and energy demand, the impact of the plant operation will still dominate over its lifetime even without ‘flood pumping’. In terms of energy demand, it seems the operational stage will always dominate, although further improvements could be investigated via efficiency measures for other operational activities. The carbon analysis however, further confirms that by far the largest proportional improvements are still made via improvements in the National Grid mix itself. This would have the potential to reduce the operational impact to below that of the construction. Hence, a decision to commission the Severn Barrage increases rather than decreases the need to implement additional low carbon energy generating technologies in the UK.

This case study highlights the necessary interactions between the analysis of individual technologies and of the national supply overall. Development of a temporally dynamic strategy for the UK energy future must be iterative. To, at least, exemplify this approach a further LCA case study was completed on an established but under exploited individual technology, that of industrial CHP, and the potential relationship between these two technologies was explored.

CHAPTER 7. INTRODUCTION TO COMBINED HEAT AND POWER

> *"But why don't they just use the heat wasted by power plants for something useful?"*
>
> \- John Miles, 2011

7.1 IN THIS CHAPTER

A brief account of the history of CHP in the UK energy sector, inclusive of its current capacity is given. Descriptions of the technologies current and potential application in both the domestic and industrial sectors are given and the case against CHP as a low carbon energy generator is summarised. A review of assessments previously completed on various CHP types is carried out and the need for a further LCA of industrial CHP is justified.

7.2 INTRODUCTION

Conventional electricity generation will typically involve the combustion of a fuel, coal or gas, which produces heat, which is used in some way, often to create steam, to turn a turbine and much of the heat is released as waste. Combined heat and power technologies, CHP, or co-generation technologies aim to use the primary fuel more efficiently by capturing the heat produced in electricity generation, or, to put it conversely, simultaneously generate electricity in the production of useful heat. Heat is, of course, an essential energy resource in its own right and the clean and efficient provision of heat in our homes and factories is intrinsic to the future low impact UK energy system. Heat is a low exergy energy source in comparison to electricity, i.e. its ability to do 'useful work' is less than implied by the gross energy value. So in terms of optimal use of primary fuel exergy, it is clearly better to meet a heating demand with heat that has already passed through a higher exergy generation process, i.e. electricity generation, than directly from the combustion of primary fuel.

Excess electricity can be exported to the Grid but this is not the case with heat, so CHP units are most efficient when appropriately sized to match a continuous heat demand, or at least when heat and power demands occur simultaneously. This makes them well suited for larger scale uses where a constant processing heat is required, e.g. in a factory, greenhouse or swimming pool. CHP units can be used for domestic heating either as part of a district heating scheme, CHP-DH, where a single unit supplies heat to group of homes, or by replacing household boilers with micro-CHP units. Hence the adoption of CHP technology where there is an established heat demand appears to be a clear way forward as it meets the multiple criteria of: a continuous and local heat load, providing exergy efficient heat and energy efficient power. In fact, the harnessing of existing heat production via CHP technology was the first way that large scale power production was introduced in many European countries (International Energy Agency 2007, 236). CHP has a relatively long history in the UK and across Europe. It is particularly well established in northern European countries that have similar climates, and hence heating and cooling needs, to the UK. In 2008, 11.5% of German, 29% of Dutch and 53% of Danish electricity production was provided by CHP. In the UK, 7% of power supply was met by CHP in 2008 and has remained at that proportion every year reported since (Her Majesty's Government 2012, DUKES. Derived from data available from: Table 5.1 and Table 7A). This is still quite a significant amount, and demonstrates that CHP supply has managed to keep pace with overall UK demand (although capacity actually dropped in 2010), but it does however show that the UK CHP market is somewhat behind its neighbours.

A number of studies suggest that there is still an opportunity in the UK energy mix for further CHP uptake in the UK (Hammond and Stapleton, Exergy analysis of the United Kingdom energy system 2001) (Speirs, et al. 2010). Although CHP plants, particularly gas fuelled CHP, cannot achieve the specific carbon results of the more venerated low carbon generation technologies, that of CCS, nuclear and wind, it has the distinct advantage of being a familiar and, relatively, uncontroversial technology. CHP is a well proven technology unlike CCS, and does not incur the sort of localized objection associated with wind farms and nuclear power plants, perhaps largely because they are necessarily installed on existing developed sites (industrial and/or residential). CHP is a readily available way to contribute low carbon electricity to the Grid mix and make an immediate impact on UK emissions.

However there are some concerns about the promotion of CHP and the potential for technology 'lock-in'. It is argued by some that primary fuelled CHP systems will become an anachronism in a highly electric future (Watts, et al. 2010) and the technology is unjustified as a carbon reduction measure in the long term. If the energy sector is successful in reducing the carbon intensity of Grid electricity, there is predicted to be a point at which CHP will cease to offer any benefit over the National Grid mix and become a burden.

7.3 HISTORY OF CHP IN THE UK

The first known CHP scheme in the UK was an industrial application at the Singer factory in Clydebank in 1898. The first known successful CHP scheme with district heating supplied heat to local shops and offices in Bloom Street, Manchester in 1911. The largest and, perhaps, most well known of the UK's CHP and district heating schemes is that of the Pimlico plant in London. It was commissioned 1950 and supplied 11,000 households with waste heat from Battersea power station (Babus'Haq and Probert 1994). The original system was decommissioned along with the power station in 1983 (Battersea Power Station Community Group n.d.) but a replacement system was installed in 2006 which includes two CHP units and currently supplies heat and power to 3,200 properties and 56 local businesses (CityWest Homes 2011). In 1960, a successful industrial scheme was implemented in Derby whereby heat from Spondon power station was used to supply steam to the adjoining Courtaulds Factory (Babus'Haq and Probert 1994). The first record of a combined 'waste-to-energy' scheme application is that of the Nottingham Corporation CHP-DH which has been operating since 1972, after concerns over secure tipping space led to a preference for incineration for waste disposal, and is still the largest CHP-DH scheme in the UK (Improvement and Development Agency 2011).

Motivated by the fossil-fuel price crisis in the early 1970s, the government formed the Combined Heat and Power Group in 1975, chaired by Lord Walter Marshall (Kelly and Pollitt 2009). In the subsequent 'Marshall Reports', published in 1977 (Combined Heat and Power Group 1977) and 1979 (Combined Heat and Power Group 1979), CHP was outlined as an increasingly essential technology, as coal and gas became scarce and expensive. The reports recognized a large opportunity for CHP roll out in the UK. It was also identified that the largest barrier to CHP implementation was the expense in comparison with the unit cost of energy and that more should be done to incentivise CHP uptake so that the opportunities were not missed. The 1977 report stated,

> "…*if nothing is done to encourage CHP-DH now, we shall not, because of long-lead times, have CHP-DH networks when we need them*", (Combined Heat and Power Group 1977)

yet another sentiment from the past that resonates well today. Despite this, the group's two main recommendations that CHP-DH demonstration schemes should be set up and that a National Heat Board be established were rejected by the, then, Department of Energy (Babus'Haq and Probert 1994).

CHP expansion was slow throughout the 80s, as feared by Lord Marshall. This was despite the passing of the Energy Act in 1983 (Her Majesty's Government 1983, Energy Act) which removed the restriction that only the, then, 'Electricity Boards' could supply electricity, which allowed private generators to do so. This was intended to support the uptake of CHP however it was passed on the prediction that a nationwide heating network would be developed to match the power grid (Babus'Haq and Probert 1994). This didn't happen. Without the infrastructure to export heat, removing the restriction mainly served to encourage private power only schemes, and arguably was the start of the full scale privatization of the national energy system. This, along with the aggressive free market ethos of the decade saw energy provision move from a public service to a commodity, for which the main driver is profit margins in the short term. This coupled with the preferential subsidisation of nuclear development forced CHP schemes well out of favour.

In the 90s, climate change and fossil fuel depletion were increasingly high priorities worldwide, and the virtues of CHP with regard to both these issues began to be formally recognised again. In 1993, the UK government set a CHP capacity target of 5 GW by 2000 (Babus'Haq and Probert 1994) as part of its climate change mitigation program. However, this target was not achieved. In 2001 the Combined Heat and Power Quality Assurance program, CHPQA, was established with the remit of encouraging CHP in the UK and certifying those schemes which qualify as 'Good Quality' (CHP Quality Assurance Programme 2010). The EU Cogeneration Directive sets down the standard that 'Good Quality' CHP must deliver 10% savings on primary fuel used compared to separate conventional generation (European Parliment 2004, Cogeneration Directive). Those schemes that qualify are eligible for a number of government financial support measures, for instance exemption from the Climate Change Levy, CCL (Her Majesty's Government 2010, DUKES. para. 6.5). In 2004, the UK government set another goal of installing 10 GW(e) of 'Good Quality' CHP capacity by 2010 (Her Majesty's Government 2004, Stratergy for Combined Heat and Power to 2010. Executive Summary, para. i). That goal was also not reached. The slow uptake of the technology has since been blamed on the decreasing 'spark spread' which is the price difference between the primary fuel, predominately gas, and the electricity produced (Her Majesty's Government 2010, DUKES. para. 6.10). This price difference is crucial to assessing the economic viability of a new scheme. However, others go further and say that the liberalization of the UK energy system has lead to volatility and uncertainty, so developers and investors continue to favour low cost, high return schemes, which exclude CHP. Furthermore, sluggish and electricity centric provision of subsidies by the government have served to exacerbate this, rather than alter it (Babus'Haq and Probert 1994). For instance, the exemption from the CCL only applies to the power generation so does not inherently incentivise the incorporation of heat recovery for low carbon generators nor does it appropriately compensate for the additional infrastructure and fuel costs associated with a switch from a heat only to a CHP system. In May 2009, the consultation on the Heat and Energy Saving Strategy closed (Her Majesty's Government 2009). No further capacity target was set. The CHPA and other pro-CHP groups expressed disappointment in its lack of support for CHP (Dialogue by Design Ltd 2009).

7.4 UK CHP PENETRATION NOW AND INTO THE FUTURE

In 2010, UK CHP schemes generated 26 TWh(e) and 48 TWh(th) of power and heat respectively, contributing 7% of the UK electricity supply capacity (Her Majesty's Government 2012, DUKES. Derived from data available from: Table 5.1 and Table 7A) plus 6% of the total heat energy consumed in that year (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14). In 2011 the amount of electricity generated by UK CHP schemes increased slightly to 27 TWh, which still continued to contribute approximately 7% of the national electricity supply capacity (Her Majesty's Government 2012, DUKES. Derived from data available from: Table 5.1 and Table 7A). Final figures for heat consumption beyond 2010 have not yet been published so this was used as the reference year for analysis.

In the last and current decade, strategizing for the future UK energy provision has focused almost exclusively on the 80% carbon emission reduction that became legally binding in 2008 (Her Majesty's Government 2008, Climate Change Act). Analysis work to this end has been heavily scenario based. Hence assessing the potential for any particular energy resource or technology should arguably be done with reference to existing scenario work. In 2010, academics from the University of Surrey and Imperial College London jointly published the report, 'Building a roadmap for heat: 2050 scenarios and heat delivery in the UK' (Speirs, et al. 2010). The report reviews four sets of scenarios from the Committee on Climate Change, Defra, DECC and UKERC and highlights the 'all electric consensus' of the work reviewed. However, the potential flaw identified in all the modelling work reviewed is the emphasis on carbon emissions which leads to low carbon but not necessarily low fossil fuel or low energy, or low impact, recommendations. Hence, it is argued that the modelling fails to acknowledge the benefits of CHP and/or district heating schemes with regard to fuel efficiency but also the more subtle benefits such as, energy diversity at the point of consumption (or rather the disbenefit of being total reliant on electricity), the reduced additional infrastructure required (compared to wind farms, nuclear, CCS etc), the reduced need for network balancing which is created by the diverse technology mix and the reduced need for individual behaviour change (which is associated with household changes such as insulation and/or heat pump uptake.)

The most recent relevant legislation was the heat strategy (Her Majesty's Government 2012, The Future of Heating) published March 2012. CHP is acknowledged as an energy efficient technology which could provided much needed help to decarbonise UK industry up to 2030 i.e. in the short term as that's only 17 years away. Fuel switching and other innovation in terms of manufacturing method improvements and/or CCS uptake are listed as equal options. In the domestic and service sectors, insulation is emphasized as the priority mitigation measure, but in the context that this will make *both* heat pumps and CHP more viable.

7.5 DOMESTIC HEAT

In 2010, domestic and service sector energy consumption accounted for 44% of the UK overall energy demand, that is, 564 TWh in the domestic and 201 TWh in the service sectors out of an overall figure of 1740 TWh (Her Majesty's Government 2012, Energy Consumption in the UK. Derived from data in Tables 1.2 & 1.4). Domestic and service sector greenhouse gas emissions accounted for only 30% of the UK total in the same year, that is, 175 Mt.CO_2 (equivalent) out of a UK total of 588 Mt.CO_2 (equivalent) (Her Majesty's Government 2013, Final UK Emission estimate. Table 3). This discrepancy is obviously mainly because not all emissions are directly attributable to energy consumption, for instance 17 Mt.CO_2 was generated by waste management in 2010. However, it is also because 80% of the energy demand in the domestic and service sectors, that is 610 TWh(th), was heat demand (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14)(for space and water heating and for cooking) and 78% of that, 474 TWh(th), was met by natural gas. Natural gas is a low carbon option in comparison with other fossil fuels and, in most cases, would have been burnt at point of consumption, hence avoiding distribution losses. Figure 55 shows the percentage split of the different fuels that met the 2009 UK domestic and service sector heat demand, and shows that gas dominates. Figure 56 shows the fuel split for the remaining non-heat energy demand and that it is almost completely met by electricity.

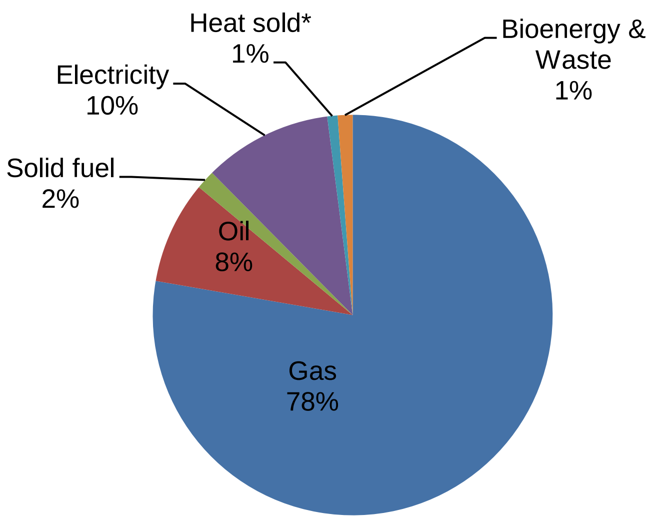

Figure 55 Domestic and Service Sector Heat Energy Consumption by fuel consumption, 2010 (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14)

*** 'Heat sold' refers to heat bought in from outside the sector under contract e.g. power led CHP plants**

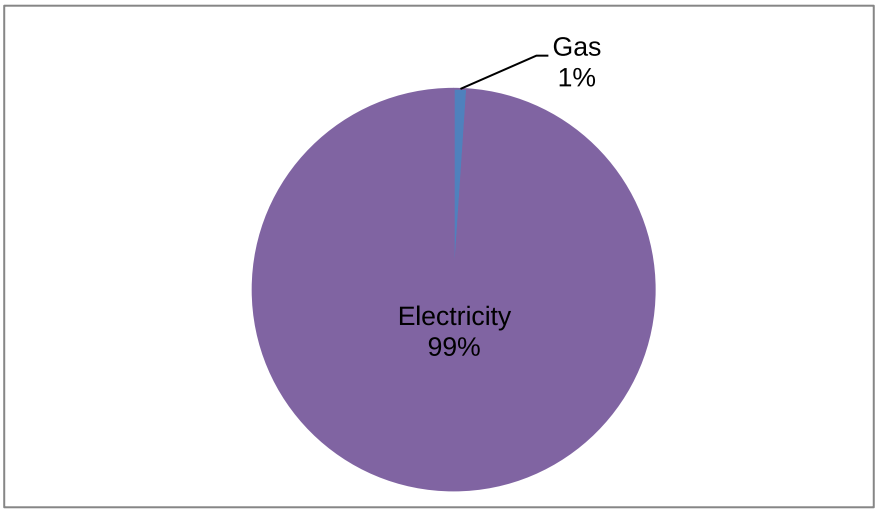

Figure 56 Domestic and Service Sector Non-Heat Energy Consumption by fuel consumption, 2010 (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14)

Given this large heat demand and corresponding power demand for all other non-heat energy needs, there would appear to be case for further CHP application. 286 CHP schemes were operating in the domestic and service sector in 2010, which includes agricultural, community and leisure schemes. These schemes made up 4% of UK CHP power capacity and 2% of UK CHP heat capacity in that year. Actual generation reached 0.8 TWh(e) of power and 1.3 TWh(th) of heat in 2010 (Her Majesty's Government 2011, DUKES. Table 6.8).

There are two ways the CHP technology can be used to supply heat to residential households and/or commercial and institutional buildings (e.g. shops, offices, universities): 1) via a single CHP unit that delivers heat to a group of buildings via a district heating network, CHP-DH, or 2) via individual micro-CHP units installed per household or small building.

7.5.1 DISTRICT HEATING NETWORKS

The implementation of district heating schemes requires local government or community compliance and usually, actual action. Reasonably large localized infrastructural work is required in order to install the CHP unit and ensure that the pipe network to each building is sufficient. Successful schemes have been implemented in a number of cities and communities across the UK, two of the most famous and successful being in Sheffield and Woking. This type of group action obviously requires social and financial management, however there is evidence that local authorities are become increasingly empowered to overcome these obstacles and are more likely to undertake CHP initiatives (Bolton 2011). In terms of incentives, the Feed-In Tariff is not available to CHP schemes rated over 2kW. This seems appropriate as schemes perform best when appropriately sized for local demand and any economic incentive to over size would be counterproductive, in terms of energy efficiency and impact reduction. The main barriers to the implementation of district heating networks are the onsite infrastructural work required, which can encounter resistance as they are necessarily implemented in areas where groups of people live or work.

7.5.2 MICRO CHP

Micro CHP require individual households to implement the change. These units have been identified as very attractive in terms of energy efficiency and environment impact reduction but they remain prohibitively expensive to most households (Hammond and Titley, Micro-generators: The Prospects for Combined Heat and Power on a Domestic Scale 2011) (De Paepe, D'Herdt and Mertens 2006). The FIT (Feed-In Tariffs Ltd 2009) may go some way to increasing the economic viability of the technology but micro-CHP systems but the scheme is more likely to make power only systems the more economically appealing choice. A study carried out by the Carbon Trust should that micro-CHP could make a positive contribution in 'hard-to-heat' buildings, i.e. old and/large buildings where the improvement potential of retrofitted insulation is limited, but performed poorly, in both environmental and economic terms, in small, modern, well insulated homes (Carbon Trust 2007).

This leads to the main reservation with regards to widespread domestic CHP uptake. With high grade insulation and better use of passive thermal techniques, as promoted by many engineers and by government legislation, it is likely, and desirable, that domestic heat demand will decrease, whilst power demand continues to increase. This widening gap between heat and power demand would make domestic CHP an ever increasing mismatched technology. In addition the demand reduction measures, heat only micro-technologies that use renewable energy or electricity (and hence a hopefully increasing proportion of low carbon supply) to meet domestic heat demand are becoming increasingly well established. Solar thermal and ground and air source heat pumps are likely to be recognized in the domestic RHI. Studies have shown that heat pumps in particular outperform micro-CHP (Cockroft and Kelly 2006) and, in the light of the 'all electric consensus' (Speirs, et al. 2010) are becoming the more popular solution.

7.6 INDUSTRIAL HEAT

In 2010, industrial energy use accounted for approximately 18% of the total UK energy consumption; that is 322 TWh of 1740 TWh (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.4). However, the greenhouse gas emissions associated with the industrial sector was reported to be around 33% of the UK total in 2010, that is 191 Mt.CO_2 (equivalent) (Her Majesty's Government 2013, Final UK Emission estimate. Table 3). This high proportion of emissions is due to the amount of carbon intense technologies and fuels used to generate the process heat energy consumed in the sector (McKenna and Norman 2010). Around 65%, 209 TWh(th), of the energy consumed in the industrial sector in 2010 was used for heat (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14) which is a smaller proportion compared to domestic energy demand but is still the dominant use. In 2010, 154 TWh(th) of the heat consumed in the industrial sector was derived from primary fuels, i.e. from gas, oil, solid and bio fuels and not from electricity or 'heat sold'. As in the domestic and service sectors, natural gas was the predominant fuel, fuelling 50% of the overall industrial heat demand, 105 TWh(th) (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14). A greater proportion of 21% was delivered by oil and solid fuels, 43 TWh(th), as opposed to 10% in the domestic and service sectors and 'heat sold' constituted 5% to industrial heat, rather the only 1% in the domestic and service sector. Only 3% of industrial heat was delivered by bio-energy and energy from waste, which is still slightly more than in the domestic and service sector which reached only 1% (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14).

Figure 57 and Figure 58 show the percentage fuel split for heart and non-heat energy consumption respectively for the UK industrial section in 2010. It can be seen that although there is more fuel diversity than in the case of the domestic and service sector, gas still dominates heat energy provision and electricity still dominates non-heat energy provision.

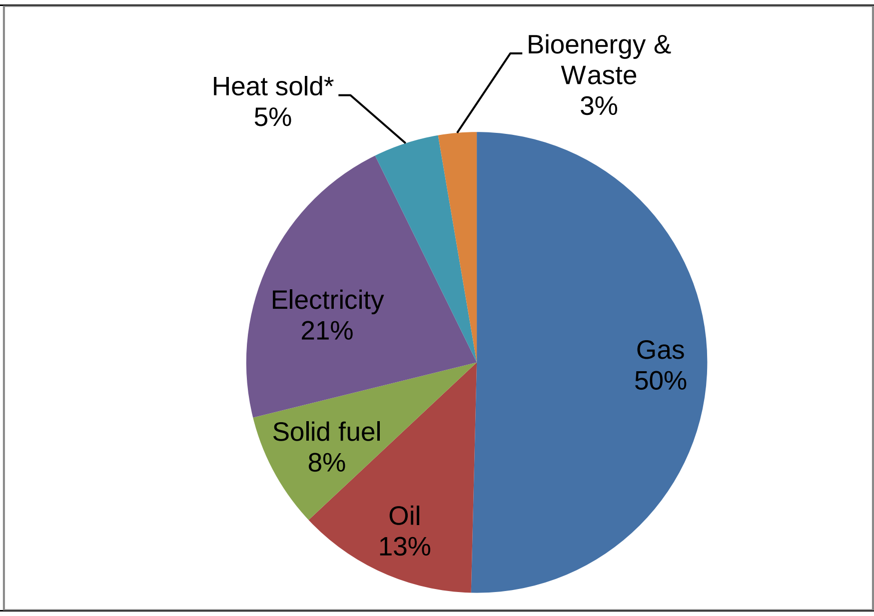

Figure 57 Industrial Sector Heat Energy Consumption by fuel consumption, 2010 (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14)

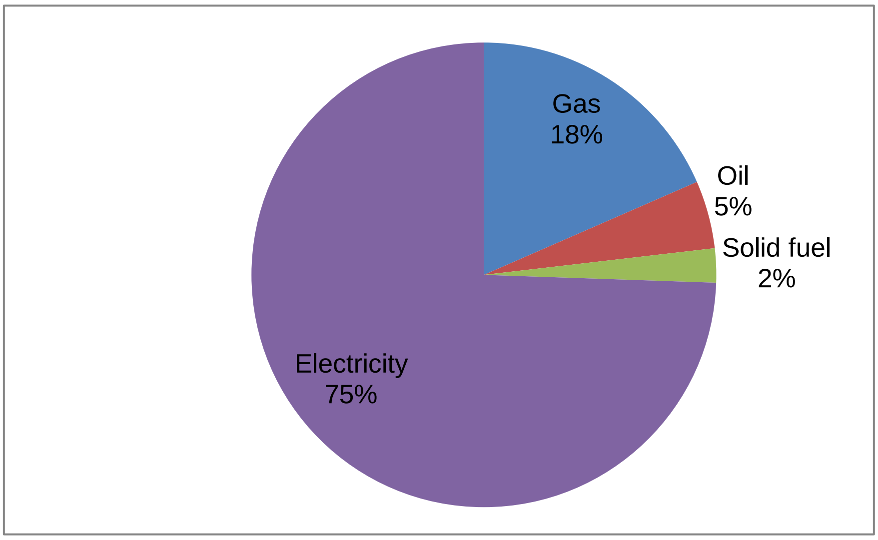

Figure 58 Industrial Sector Non-Heat Energy Consumption by fuel consumption, 2010 (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14)

It is widely accepted that current renewable and electricity heat generators are not yet able to meet the heating demands of industry, which is why the heat strategy stresses CHP as an option for industry (Her Majesty's Government 2012, The Future of Heating. para. 4.18). CHP is one way that the industrial sector could improve its carbon credentials without even changing its fuel or heat demand. This could be implemented by encouraging new factories to choose sites next to existing power stations and to make use of the waste heat, or by replacing heat only production systems at existing factories with CHPs, which can power the site itself and export surplus to the National Grid. In the UK, new factories are rarely proposed so system conversion in an existing factory would be the most likely scenario for a new scheme. The technology has already been adopted in some industrial systems across the UK to replace heat only systems. The motivation for this technology change for the site itself is often financial (International Energy Agency 2007, 238) as extra revenue generated by the power export but this driver is subject to the spark spread, as previously discussed. However, the harnessing of industrial heat demand for electricity generation may have the potential to contribute to the UK low carbon electricity future.

Following an economic analysis in 2007, Defra predicted that medium to low temperature industrial CHP capacity would be limited to 5.4 GW(e) in 2010 (AEA Technology 2007, Table 2). The actual reported capacity figure was 5.4 GW(e) for 2010 (Her Majesty's Government 2012, DUKES. Table 7.8). Defra also predicted that industrial CHP schemes would be limited to a capacity of 6.8 GW(e) in 2015 (AEA Technology 2007, Table 2). Extrapolating from this small set of figures, a maximum feasible power capacity for industrial CHP in 2050 can be set at 15 GW(e). 89% of the total UK CHP electrical capacity and 92% of the total heat capacity was within the industrial sector in 2010. The reported actual generation from industrial schemes was 24 TWh(e) of power and 44 TWh(th) of heat in 2010 (Her Majesty's Government 2012, DUKES. Table 7.8). Extrapolating the reported figures, a maximum of 66 TWh(e) can be set for industrial CHP for generation to 2050. This implies a maximum additional generating potential of 42 TWh(e).

The power capacity of industrial CHP will also be limited by the available heat load. If it is assumed that all of the heat generated by industrial sector CHP was consumed within the sector, then the 110 TWh(th) of remaining heat derived from primary fuels was not supplied by a CHP installation in 2010. This energy is highly unlikely to be fully available for CHP application as there is no accounting for the likely technical and economic limitations, also it does not make any consideration for the potential industrial heat demand that could be met via CHP generated electricity. However, this figure can be used as an estimate for the maximum additional industrial heat demand available for CHP application.

7.7 CHP AND BIO-FUELS

Bio-fuel, refers to fuel derived from anything that can be produced on the earth's surface so anything that can be grown, e.g. wood, straw, sugar cane, or anything that is produce as waste, e.g. municipal waste, sewage. Bio-fuels have driven the development of the human race right up until the industrial revolution, and still are the main sources of fuel in most human settlements across the globe today. Switching to bio-fuels is advocated as another way that UK heat supply could reduce its environmental impact. However, a fuel switch could be made in conjunction with the conversion to CHP generation, and thus generate low impact heat and power. In fact, one of the environmental advantages of CHP technologies is that they are able to make use of bio-fuels which can have a poorer calorific quality and, hence, can be unsuitable for conventional power plants.

Bio-fuels can be considered renewable if consumption is managed such that it is in step with the rate at which bio-fuels can be replenished. They are low carbon because their production and combustion can feasibly be kept in line with the natural carbon cycle of the earth's surface. The carbon dioxide emissions in combustion of an amount of bio-fuel can be sequestered in the production of an equivalent amount. Bio-fuel production has curried controversy because of the perceived competition for land and resource between energy crops and food. However, this concern does not apply to waste streams. The infrastructure for generating fuel from waste streams is improving. CHP can play an important role in exploiting this resource with the added benefit of heat and power outputs and, in this way, providing a holistic solution to industrial needs.

7.7.1 UK BIO-FUELS

In 2010 6% of the fuel consumed in the UK CHP stock was from bio-fuel, this was a 1% increase on 2009 and is reported to be due to increases in the use of sewage gas and wood fuels (Her Majesty's Government 2011, DUKES. para. 6.17). UK bio-fuelled CHP schemes will typically use either bio-mass, wood chip or solid waste, or bio-gas which is derived from biomass, via anaerobic digestion or forced gasification and/or pyrolysis.

Bio-mass schemes can be particularly convenient for decentralized, rural applications where localized waste and/or wood resources are the most easily available fuel and import of a 'conventional' fuel would have additional environmental and economic consequences. Conversely, bio-mass fuelled plants can also be ideal for large urban areas where waste disposal can become most problematic, as in the Nottingham installation (Improvement and Development Agency 2011). The biggest disadvantage associated with biomass schemes that gaseous and particulate emissions, other than carbon dioxide, can be worse than 'conventional' fuels and may lead to localized air quality issues.

Bio-gas however, has the distinct advantage that it can be purified to a sufficient quality to be injected into the existing national gas grid, hence existing gas fuelled plants can switch to bio-gas without any additional on-site changes. In 2009 the UK National Grid published a paper on the potential for incorporating bio-gas into the system (National Grid 2009) which stresses the advantages of this approach over the additional logistics required to distribute bio-mass and the reduced need for any changes from the consumer. The paper recommends gas extraction from landfill and sewage systems over domestic organic waste collection for the same reason; it avoids individual level behaviour change. However, householders are already being asked to make significant changes to the way that they manage their waste due to recycling targets and increases in landfill tax. For instance in Bath, organic kitchen waste collection has already been implemented in preparation for the tax rises (Bath & North East Somerset Council n.d.), which will reach £80 per ton by 2014. The waste is then converted either to bio-gas or compost (New Earth Solutions 2012). If bio-gas is suitable purified it can have the same energy quality and reduced localized emissions as natural gas. The main disadvantage of bio-gas over bio-mass is the additional infrastructure and processing required to produce it and purify it to National Grid quality.

The IMechE have been advocating the uptake of energy-from-waste schemes, exclusively via CHP, as a solution to both responsible waste disposal and sustainable energy (Institution of Mechanical Engineers 2006).

7.8 THE CASE AGAINST CHP

The Cogeneration Directive (European Parliment 2004, Cogeneration Directive) sets down the standard that 'Good Quality' CHP must deliver 10% savings on primary fuel used compared to separate conventional generation e.g. via a gas boiler and the National Grid. However, it is argued (Watts, et al. 2010) that this sort of standard implies that heat and electricity are of equal value when it comes to efficiency and masks the fact that electricity can be far more energetic, or exergy rich, than heat. So whereas it might be the case that a CHP unit will generate more heat *and* power from the same amount of fuel, it will generate much less electricity than if the fuel was invested in electricity generation alone. So, arguably, useful heat comes at the cost of the lost electricity. However, if there is a clear demand for the heat then the distinction between exergy and energy seems irrelevant, and exergy analysis alone in the analysis of heating technologies has been judged as insufficient (Hammond and Stapleton, Exergy analysis of the United Kingdom energy system 2001), hence the reduction in electricity production per unit of fuel consumed can be considered appropriate if all the heat is used. The danger in this is that the desire to 'use-up' all the heat in order to justify the electricity might detract from the preferential path of increase insulation and passive heating. However, as discussed above, building regulations are in place in the domestic sector that are specifically design to reduce the heat demand, and because of this alone, CHP is increasingly being regarded as the wrong solution for sustainable domestic heat.

It has already been outlined why existing industrial sites with an established heat load might be preferentially selected for CHP conversion. However, this will of course lead to an increase in primary fuel demand over the previous heat only system. So perhaps, the real question then becomes, is the additional infrastructure and fuel required over a heat only system 'worth it' for the additional electricity generation? The answer to this question lies in the analysis of the power in the context of the supply it displaces, and perhaps this is the most interesting consideration. As electricity generation becomes decarbonised it is predicted that there will come a point where it is 'cleaner' to obtain heat from electricity than it is from a primary fuel. Enthusiasm for electric heating, specifically heat pumps as the solution to the UKs heat demand has risen dramatically in the last 2-3 years, this is perhaps with the rise in optimism that the electricity network could really supply low impact power.

With regard to fuel switching, if we can generate heat from bio-fuels, perhaps it is preferable to simply convert heat only systems to bio-fuel rather than to a bio-fuelled CHP which will increase the overall fuel demand. It is argued that the implementation of bio-fuelled CHP would put unnecessary stress on the bio-fuel feedstock at a time when it is still proving its potential as a serious energy solution. Arguably waste is a plentiful feedstock, but there is concern that developing an energy system that is reliant on waste may detract from the need to reduce and recycle, which according to the waste hierarchy should take priority. A Swedish LCA study showed that while waste fuelled CHP systems performed better than natural gas and waste incineration was typically better than landfill, reuse or recycling of waste was nearly always preferable to incineration of any type (Eriksson, et al. 2007). Furthermore, if a legitimate bio-fuel feedstock is established it is arguably better devoted to meeting the needs of the transport sector for which there are fewer feasible alternative options.

7.9 REVIEW OF PREVIOUS CHP ENERGY AND ENVIRONMENTAL ASSESSMENTS

A number of studies have been previously completed on CHP units to investigate their environmental impact and the carbon saving potential that they could offer. Variations in approach to inventory analysis are considerable, as is normally the case when comparing modelling of any sort. However, what is of particular interest, in the context of CHP assessment as a low impact power generator, is:

1) The method of impact allocation between heat and power generation and

2) The alternative power generation that is used as a comparison to calculate impact savings

The UK government reported that the electricity generated by UK CHP systems saved 9.28Mt.CO_2 (equivalent) in 2010 against the total 'UK basket carbon intensity', i.e. against the same amount of power generated by the National Grid full mix of electricity generators, including nuclear and renewable (Her Majesty's Government 2011, DUKES. Table 6H). The method used to allocate emission intensity between heat and power is based on the adopted method of fuel demand. This assumes that electricity generation is half as efficient as heat generation and therefore fuel demand, and hence emissions, can be allocated using a simple ratio of 1:2 (Her Majesty's Government 2011, DUKES. para. 6.9). This allocation method would lead to discounting the emissions associated with heat with respect to a heat only generation system, hence this method can only really be justified in instances where there is a direct demand for both the heat and power. EcoInvent completed a LCI of a 160kW(e) cogeneration unit (Heck 2007) which formed the basis of all the subsequent EcoInvent CHP infrastructure data entries, including a 'Mini CHP' unit (Primas and Hofmann 2007). This infrastructural data set is combined with a Swiss natural gas supply to generate data sets per unit of heat and power. In contrast to the DUKEs calculation, of course, is that EcoInvent use a life cycle approach which accounted for up and down stream impacts, i.e. construction and disposal, rather than just operation. The EcoInvent database options allow for various allocation methods. The fuel can be allocated either: via exergy, in which the majority is allocated to the electricity, via energy, in which the split is more even, or via heat, in which the electricity is assumed a 'bonus' and no fuel is allocated to the power generated at all. The plant infrastructure which is common to both heat and power production is allocated in a similar way but that which is solely required for power, is never allocated to the heat output. The report for the EcoInvent mini CHP unit, states that,

> "*Allocation is a decisive issue for the description of combined heat and power production and its choice may depend on single application or motivations of the analyst*"(Primas and Hofmann 2007).

This suggests that allocation is open to the interpretation of the analyst, given the particular context of their study. Interestingly however, there is no published dataset for a power allocation, thus suggesting that EcoInvent do not believe that heat could, or perhaps, should, be considered a by-product of power generation. This is supports the presumptions discussed above that CHP should only be implemented where there is an established heat demand.

In summary, the allocation methods adopted in the reviewed studies, in likely decreasing order of allocation to power, are:

- Using a 1:2 ratio, assuming that power is twice as impactful as heat. This method is referred to as the 'DUKES' method for the rest of this thesis
- By exergy content, which would lead to a higher allocation to power
- By energy content, which would simply depend on the generating capacity
- By heat only, which would lead to no impact allocation to power at all

A study completed by MaxFordam (Watts, et al. 2010) criticizes existing analyses for calculating carbon and impact savings of power generated by gas CHP systems via comparison with the current Grid mix only, as the UK government calculations do (Her

Majesty's Government 2011, DUKES. para. 6.28), which would include a large proportion of coal fired generators. They argue this gives an unfairly favourable result for gas fired CHP as it does not address whether this the most (carbon) efficient way of using gas at all, nor does it lend any insight into the role of CHP in the potential decarbonised electric future. However, it has proved hard to find a study that only compares CHP power generation to the current National Grid mix, as the MaxFordam report describes. In 2006, a Belgian study assessed the environmental performance of five types of domestic micro-CHP units (De Paepe, D'Herdt and Mertens 2006). The impact reduction was calculated via comparison with heat from household gas boilers (at 90% efficiency) and electricity supplied by the 'Grid'. Three technology options where included to represent the 'Grid'; these were a combined cycle gas turbine, CCGT, an average Belgian fossil fuel plant and an average Belgian plant which includes considerable nuclear stock. Another domestic micro-CHP study from the University of Bath made comparisons only with gas boilers and CCGT, and no comparison was drawn with any other fossil fuelled generation or supply mix(Hammond and Titley, Micro-generators: The Prospects for Combined Heat and Power on a Domestic Scale 2011). These studies both successfully demonstrated the environmental advantages of gas CHP in comparison to other gas systems. However, they do not provide any comparison to potential future low carbon power supplies. These two studies also were carried out on the assumption that there was equal demand for heat and power that could be meet by the CHP units being assessed so did not need to consider the problem of allocation.

7.10 SUMMARY

The rise and fall of CHP uptake in the UK can be fairly easily reconciled with the changing socio-economic landscape of the UK energy system. It first appeared in the UK in the quintessential era of British innovation in the late 1800s. Its practicality and efficiency appealed greatly to the post war Britain in the 50-60s, and bright predictions for its future were made on the basis of assumed continued national and local government support. The fossil-fuel price crisis of the 70s prompted increasing pressure that CHP was in fact necessary, rather than just appealing. However the liberalisation of the energy market saw the technology fall out of favour in the 80s as faster return electricity only generation technologies took preference. More recently, the dual concerns of climate change and energy security have triggered renewed interest from government, industry and local communities.

Domestic CHP and district heating systems are wide spread in Northern Europe and there is further potential for uptake in the UK, particularly with the apparent empowerment of local governments and communities to undertake localized climate mitigation and energy security measures. However, the infrastructural work required to retrofit in existing housing stock and the high building regulations of new builds, suggest that the domestic sector should not be the primary arena for additional CHP implementation.

The UK industrial sector contributed 33% of the national greenhouse gas emissions in 2010 (Her Majesty's Government 2013, Final UK Emission estimate. Table 3). This is due to the high proportion of carbon intense fuels used to generate heat. Industrial process heat supply is ideal for the application of CHP, as the technology is most efficient where there is a constant and 'real' heat demand. Hence, the area where large scale capacity increases are most feasible, and are most needed, will be in industry where there is an established demand for heat.

However there are concerns that the uptake of new CHP systems now will result in a technology 'lock-in' and lead to carbon costs in a decarbonised electric future. Conversion from a heat only system to a CHP system will inevitably lead to an additional fuel demand and carbon emission in exchange for the benefit of power generation. The significance of these additional impacts depend on the electricity supply that the generated power is assumed to displace. Existing environmental studies of CHP system have not fully investigated or discussed the environmental impact of the power generated now versus the future. Hence, it was decided that closer examination of the potential role of CHP, specifically the exploitation of established industrial heat loads for the generation of power, in the context of a potential decarbonised electric future was required.

CHAPTER 8. LCA CASE STUDY: WINNINGTON CHP PLANT

8.1 IN THIS CHAPTER

This chapter is a full report on the LCA carried out on the existing, E.On operated, natural gas fired, industrial CHP unit in Winnington, UK. The focus of the assessment is on the power generated by the plant and this is within the premise that the power is generated as an additional benefit via harnessing the heat load that would have been produced anyway. Appropriate allocation methods are explained for investigating the impact of the power within and without the context of this premise. Detailed Inventory Analyses of both the plant itself and that needed to assess the hypothetical separate systems required to appropriately apply the allocation methods is given. A Results Interpretation that is in line with that carried out for the Severn Barrage study is presented. Additionally, attention is paid to how the impact savings in operation compare with the energy consumed and carbon emitted in the technology conversion process

8.2 OVERVIEW OF WINNINGTON CHP PLANT

The case study CHP plant was constructed, commissioned and handed over to its current operators in 2000, under a 20 year contract agreement. The plant is under contract to supply a local soda ash works with 280 MW(th) in the form of intermediate and low pressure steam, which equates to 2,453 GWh of heat a year. Power generation is limited to 104 MW(e), giving an annual power generation of 911 GWh (around 75 MW(e) is supplied to the National Grid after the power demands of the soda ash works and the site itself have been met). Gas consumption is reported to be 3,942 GWh per year. The water consumption for steam production is around 8.5 Mt per year and is approximately 50% 'raw' water, which is drawn from two local reservoirs, 36% waste hot water from the soda ash works, a maximum of 1% potable water and 12% condensate return from the steam supplied. An additional average of 8.3kt a year of 'raw' water is used for 'quench' water on site, that is to reduce the temperature of waste water before it is allowed off site (Gibson, Dutton, et al. 2011).

The primary purpose of the plant is to meet the contracted steam supply and the financial penalties for steam interruption are severe. Hence, delivering heat that is 'wasted' by, or a by-product of, power generation is not a feasible option. This makes the scheme different from what might typically be thought of when talking about CHP schemes, i.e. a scheme where there is at least an equally important demand for heat and power. The power generated is a by-product of the heat generation, which would otherwise be met by a heat only system, and was introduced to improve the economic viability of the plant. In fact, the generators run at less than full capacity as the power is limited to match the heat demand.

The plant consists of: two GE 6B 40 MW gas turbines, two heat recovery boilers, one 60 MW back pressure steam turbine, a water treatment plant, a polisher or de-aerator unit for satisfactory condensate return and three back-up auxiliary boilers. Figure 59 shows a process diagram of these components. Site assets also include the steam and power mains that connect the CHP Plant with the soda ash works site and the National Grid.

The site has one of the largest water treatment plants in the UK. The low levels of condensate return from the customer requires the site to source large amounts of 'raw' water from local natural sources to make up the total water required to maintain the steam supply, i.e. it is an 'open loop' water supply. This raw water has a high concentration of organic matter, especially in the winter and in times of excessive rain fall. This raw water has to undergo considerable processing to meet an appropriate standard for use in steam production and hence an extensive treatment plant is required (Gibson, Dutton, et al. 2011). If a higher level of condensate return could be ensured then the additional raw water demand could be reduced, or even completely removed, and the water treatment infrastructure could be scaled down. This 'open loop' arrangement is not typical in UK CHP plants, nor is the high raw water demand, hence why no other UK CHP has a treatment plant of this scale.

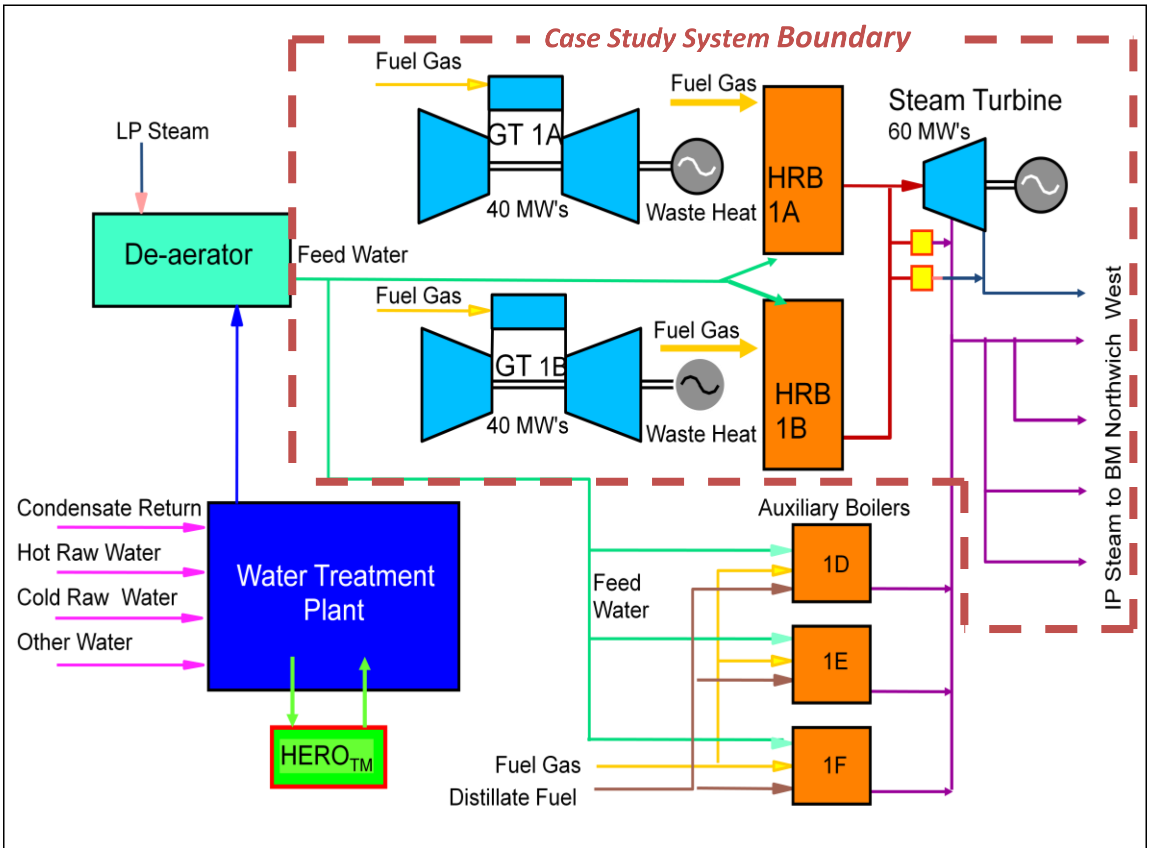

Figure 59 Process diagram of the case study CHP system (Gibson, Winnington CHP 2011)

8.3 GOAL AND SCOPE

The primary purpose of this case study is to assess and analysis the life cycle environmental impacts of the power generated via the exploitation of an established industrial heat demand. A site specific model was developed for an existing UK CHP plant using data collected on site visits and via discussion with plant engineers. Remaining data gaps are filled using the EcoInvent (EMPA 2007) database. The premise of this case study is that CHP technology is adopted in preference of a heat only system for the exploitation of an established heat load for the bonus of power generation. It is assumed that no existing, functional plant is displaced, i.e. that there is no pre-existing heat only system or that the new CHP system is adopted at the natural end of life of the previous heat only system. Hence, there is no requirement to include the decommission or disposal of any previous heat only system in the case study LCI. Once a satisfactory model has been established, then the effects of switching to an alternative fuel, specifically bio-gas, can be investigated.

One of the main considerations of the study is the impact differences of the CHP scheme with reference to the, hypothetical, heat only system that would have been installed to meet the steam demand if there was no desire to simultaneously generate power. A model was also developed to represent this alternative system so that comparisons could be drawn as accurately as possible.

8.3.1 STUDY BOUNDARIES

The CHP plant is assumed to have lifespan of 30 years. The CHP inventory is developed within the constraints of providing a representation of the actual case study plant, a usable model for the average UK gas fired CHP plant and a fair comparison against the heat only model. With this in mind the data provided by the site is used as a guide but anything that appears to be unique to the particular running of the study plant and is outside the direct requirements of the CHP system is excluded. As a result, the three back-up boilers, the de-aerator and the auxiliary energy or resource demands associated with plant staff and buildings are excluded from the model. The extensive water treatment system present at the site is also not explicitly modelled, however treated 'tap water' is included in the inventory to be in line with typical CHP water usage, see Section 8.4.1 . The electricity demand of the site itself is met by the plant, however whether the power generated is consumed on or off site is irrelevant to the assessment. The hardware included in the inventory is indicated by the Case Study System Boundary marked on Figure 59.

The major difference between this study and that of the Severn Barrage is that the case study CHP plant already exists, hence the inventory analysis need not be speculative. There is no need for 'best' or 'worst' scenario analysis. However, once completed, the results of the case study can be used to investigate options for hypothetical installations.

8.3.2 ALLOCATION

In order to assess the impact of the electricity generated by the CHP plant, the overall lifetime impact must be allocated between the heat and power generated. As discussed in section 7.9 , the Digest of UK Energy Statistics, DUKES, allocated emission intensity between heat and power using a simple ratio of 1:2 (Her Majesty's Government 2011, DUKES. para. 6.39), which assumes that there is a direct demand for both the heat and power. When converting to a CHP from a heat only technology, as would be the case in many industrial systems, arguably the emissions allocated to the heat production should remain fixed and only the emissions that are above the previous heat only system are attributable to the power generation. This method is referred to as the 'fixed heat' allocation in the results discussions. A third method of allocation is to calculate the total relevant impact of producing an equivalent amount of heat and power using separate generating technologies and then apply the same percentage split to the total overall impact of the CHP. In all three allocation methods the overall saving will be the same, but the different associated savings with the power generation is important in order to evaluate the contribution CHP conversion can make to UK low carbon electricity supply. All three allocation methods are initially investigated, but the DUKEs and 'fixed heat' allocation methods are used throughout the impact analysis of the power generated.

8.3.3 FUNCTIONAL UNIT

For comparison with alternative heat and power systems the functional units of 'impact per lifetime relevant energy output of case study CHP' (which in the case of the case study CHP is of course the whole life cycle impact) or 'impact per annual relevant energy output'. Table 37 presents the energy quantities required for these functional units

	Annual	**Lifetime**
Heat (GWh)	2453	73584
Power (GWh)	911	27331

Table 37 Functional Units for comparison of alternative heat and/or power systems

For comparing the impact of the power generated with that of the five options for the National Grid mix, the impact allocated to power generation is resolved to the specific functional unit of 'impact per unit generated', one unit being equal to 1MWh.

8.4 LIFE CYCLE INVENTORY ANALYSIS

8.4.1 CONSTRUCTION/HARDWARE

Onsite Construction Works: No site specific data was available for the installation and commissioning activities. Hence the EcoInvent dataset for the construction works for a 160 kW(e) cogeneration unit (Heck 2007) has been used scaled according to site area.

National Grid Connection: No site specific data for the additional infrastructure required for connection to the National Grid was available so an adaptation of data from EcoInvent was used. Inventory data for the Grid connection for 30 kW, 150 kW, 600 kW and 800 kW onshore wind farms (Burger and Bauer 2007) was used to make a scaled estimate for the required connection infrastructure and its disposal.

Gas Turbine: According to data provided by E.On staff (Adams 2011), the GE 6B model has a 'packaged power plant' mass of 315 t, inclusive of the mechanical drive system (i.e. the turbine itself plus gearbox and fuel and lubrication systems) which has a reported mass of 86.4 t. Documentation obtained from site states that the gas turbine gearbox has a mass of 12t (Alstom Power 2000), hence it has been assumed that the gas turbine itself, inclusive of fuel and lubrication systems, has a mass of 74.4 t. The EcoInvent inventory entry for a 10 MW gas turbine assumes that nearly all the mass of the turbine is steel, with approximately 95% reinforcing steel and the remaining 5% chromium, or stainless, steel. This proportional split is adopted for the case study gas turbine yielding a material inventory of 4.5 t of average processed chromium steel and 69.9 t of average processed reinforcing steel. The gear box and remaining mass of the package plant, which is assumed to consist of the compressor, combustor, auxiliary starting system and other connecting parts, is simply represented as 132 t of average processed reinforcing steel.

Steam Turbine: Documentation obtained from site states that the steam turbine has a total mass of 90 t (Alstom Power 2000) and that it drives a synchronous generator via a rigid coupling, hence there is no gearbox. Data obtained from E.On staff regarding the steam turbine shows that the larger turbine sub-components, e.g. the casing and rotor, are steel and a few of the smaller sub-components, the largest of which being the blades, are stainless steel i.e. with a chromium content of more than 11% (Powell 2011), which supports the proportional split adopted for the gas turbine. Discussions with E.On staff and specialists at the University of Bath have indicated that the mass difference between the gas and steam turbines, that is 74.4 t versus 90 t, would be largely due to the thicker casing walls required for a steam turbine, hence it is assumed that the additional mass of the steam turbine is entirely cast steel, yielding a material inventory of 4.5 t of average processed chromium steel and 85.5 t of average processed reinforcing steel. Steam turbines are a simpler technology than gas turbines, so it is assumed that this is sufficient to represent the full steam turbine 'package'.

Generators: The steam turbine generator has a mass of 130 t (Alstom Power 2000), and the gas turbine generators, exclusive of gearbox, have a mass of 108.45 t (Alstom Power 2000) each. A detailed bill of materials was made available by E.On staff for the generator for the 800 MW steam turbine at the proposed Kingsnorth power station, consisting mainly of reinforcing steel, copper wire and rock wool insulation, each subjected to material appropriate average manufacturing processes, with a total mass of 575 t (Kinson 2011). This data was scaled by mass in order to represent the three generators required for the case study CHP model.

Heat Recovery Boilers, HRB: Boilers of some sort would of course be required in any industrial steam production process. The only notable difference is that the HRB in a CHP system would be rated to produce steam suitable for the steam turbine rather than for the customer's use (the steam turbine is, of course, rated so that the exhaust steam is suitable for the chemical works). One HRB in the case study CHP has a mass of 480t and is predominately steel (Alstom Power 2000). Hence a simple representation of 480 t of average processed reinforcing steel is used for each HRB. The EcoInvent database entry for 'steam, for chemical processes' (Zah 2007) accounts for hardware via the use of 'gas burned in industrial furnace' in its inventory rather than 'gas at consumer' (Jungbluth 2003).

Turbine and HRB shipping: Correspondence with the sales team at GE suggests that the steam and gas turbine components would have been manufactured in Belfort in eastern France (Pasteur n.d.). It has been assumed that this is also the case for the HRBs. Components are assumed to travel by lorry from the factory to Brest, then by container barge to Liverpool, and then by lorry again to site. This shipping schedule is modeled using transport entries in the EcoInvent database (EMPA 2007) and distance calculations from Google Maps (Google Maps 2011).

Steam mains: Two 4.8km API 5L Grad B Carbon steel pipes, insulated with a 150 mm thickness of rock wool connect the CHP plant with the soda ash works in order to deliver the steam.

Water Treatment Plant, WTP: Specific data for the chemical and water requirement of the WTP were made readily available, however no detailed inventory data on the hardware requirements has been identified. Hence for this model it is assumed that all water is 'tap water' for which the EcoInvent database entry (Jungbluth, N 2005) inherently accounts for all hardware, process and chemical requirements. This is also in line with the inventory of the EcoInvent database entry for 'steam, for chemical processes' (Zah 2007).

Table 38 presents all the life cycle inventory data collated for the construction stage of the Case Study CHP plant.

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Component/ EcoInvent dataset	*Material*	*Quantity (tonnes)*	*Scaling Factor*	*Supplier location*	*Journey*	*Transport Type*	*Distance (km)*
ONSITE WORKS							
'Construction work, cogen unit 160kWe/RER/IU'(Heck 2007)		n/a	280	n/a	n/a	n/a	n/a
NATIONAL GRID CONNECTION							
Edit of 'Wind power plant 800kW, moving parts/RER/I U' (Burger and Bauer 2007)	Aluminium	0.00004	12.3	n/a	n/a	n/a	n/a
	Copper wire	15					
	Polyethylene	7.3					
	PVC	5.3					
	Steel bar, low-alloyed	0.063					
	Lead	0.0005					
	Tin	0.0005					
	Polypropylene	0.02	1				
GE 6B GAS TURBINE x2				Belfort, France			
Turbine plus fuel & lube systems	Machined steel	69.9	n/a		Belfort, France – Brest, France	Road	1047
	Machined stainless steel	4.5					
Compressor	Machined steel	120	n/a				
Combustor							
Bearings							
Auxiliary starting system							
Hydraulic supply system							
Electronic control system							
Dry low NoX system							
Gear box	Machined steel	12			Brest, France – Liverpool, UK	Ship	723.35
ALSTROM BACK PRESSURE STEAM TURBINE							
Turbine plus fuel & lube systems	Machined steel	85.5	n/a				
	Machined stainless steel	4.5					
GAS TURBINE GENERATOR x2							
Stator: from Kingsnorth Inventory, for 800MW ST	Rolled steel sheet	300	0.189				
	Steel plate	65					
	Copper wire	75					
	Rock wool insulation	5					
Coolers: from Kingsnorth Inventory, for 800MW ST	Copper finned tubes	24			Liverpool, UK – Winnington, UK	Road	47.83
	Steel tubes	10					
Rotor: from Kingsnorth Inventory, for 800MW ST	Machined steel	70					
	Copper drawn bars	24					
	Glass fibre insulation	2					
STEAM TURBINE GENERATOR							
from Kingsnorth Inventory, for 800MW ST	As above	As above	0.226				
HEAT RECOVEREY BOILERS x2							
Heat recovery boiler	Machined steel	480	n/a				
STEAM MAINS							
Pipework	API 5L, carbon steel, 50cmOD	9.6 km	n/a	n/a	n/a	n/a	n/a
Insulation	Rockwool insulation, DN 400, 30 mm	302 km					

Table 38 Table of life cycle inventory data for the construction stage of the case study CHP

8.4.2 OPERATION AND MAINTENANCE

Fuel: the fuel type is represented by, 'natural gas, high pressure, at consumer /GB' taken from the EcoInvent database (Jungbluth 2003).

Lubrication oil: No measured data was available for the actual oil consumption for the case study plant. Published studies of gas fired cogeneration plants provide values of 0.5 mg/MJ_{In} (Primas and Hofmann 2007), 0.1 g/kWh(e) (Nadal 1997) or 0.4 g/kWh(e) (Heck 2007). In accordance with the precautionary principle the, latter estimate was adopted as it yields the greatest total consumption of 11 Mt over the plant's 30 year lifetime.

Emissions and Waste: Annual emission and waste production data was taken from the 'Pollution Inventory Reports' submitted by the plant to the Environment Agency. The greenhouse gas and particulate emissions are caused by the combustion of the gas. There is limited information available as to the nature of the toxic waste but this is probably used oil and the sludge produced by the water treatment plant, so it is possible that its inclusion could lead to some double counting as the water is assumed to be 'tap water'. However, as a breakdown of the exact nature of the waste was not available, an average toxic waste mix was included for the full reported amount. Similarly, as no detailed information of the sources of the municipal waste was available, an average mix of the full reported amount is included.

Table 39 presents the quantities of the main inventory flows identified for the operation stage of the Case Study CHP, i.e. all data collated exclusive of 'deliveries to site'.

	Unit	Annual Amount	Lifetime Amount (30y)
OPERATIONAL FLOWS IN: RESOURCE			
Fuel (Natural Gas (Jungbluth 2003))	GWh	3 942.0	118 260.0
Lube Oil	T	364.4	10 932.5
Water ex. Condensate return (Tap Water (Jungbluth, N 2005))	Kt	4 347.5	130425.0
Deliveries	km (road)	17 325.9	519 777.8
	km (ship)	4 156.4	124 690.9
OPERATIONAL FLOW OUT: EMISSIONS & WASTE			
Carbon dioxide	Kt	751.0	22 530.0
Carbon monoxide	t	159.5	4 785.0
Methane	t	53.5	1 605.0
Nitrogen oxides	t	351.5	10 545.0
NMVOC, non-methane volatile organic compounds	t	13.0	390.0
Particulates, <2.5 um	t	8.6	258.0
Particulates, >10um	t	11.6	348.0
Sulfur dioxide	t	41.8	1 254.0
Toxic waste	t	51.6	1 548.0
Municipal waste	t	145.4	4 362.0

Table 39 Table of life cycle inventory data for the operation stage of the case study CHP

Deliveries to site: An estimate for the annual transportation of goods to site was calculated using a list of postcodes of the origin of all deliveries to site for the year 2011 from the site records. For each postcode the driving distance to site was estimated using Google Maps (Google Maps 2011) and that distance was assumed to be traversed by a '16-32 t truck' or a ‘transoceanic freight ship’ where appropriate. The results of these calculations are presented in Table 40. Any delivery vehicle arriving on site would also have to make a return journey but also vehicles would typically make multiple deliveries in a trip. This level of detail is not available so only allocating the outward journey was deemed to be satisfactory compromise.

Supplier location	Transport Type	Distance	No of deliveries	Total Distance
OX14 1DY	Road	242	6	1452.0
S18 1DJ	Road	101	7	707.0
BL9 6YA	Road	59	3	177.0
NE28 9ND	Road	279	2	558.0
France	Road	400	1	400.0
	Ship	500		500.0
WF12 9QT	Road	99.8	1	99.8
NG11 0EE	Road	118	1	118.0
ME10 2SG	Road	380	1	380.0
SO40 3NB	Road	342	1	342.0
SL1 4UE	Road	279	1	279.0
KY4 OAE	Road	401	1	401.0
YO18 7JA	Road	201	1	201.0
NE28 9ND	Road	279	1	279.0
SK6 2SU	Road	46.1	3	138.3
WN2 4EZ	Road	41.2	1	41.2
AB21 7EZ	Road	584	1	584.0
ST15 ORS	Road	62.5	1	62.5
CH5 2HN	Road	45.5	2	91.0
CH5 2QR	Road	44.7	1	44.7
CW9 EEH	Road	4.8	2	9.6
TN9 1RF	Road	371	1	371.0
CB4 5WE	Road	266	2	532.0
PA1 2BH	Road	378	1	378.0
WA7 1PT	Road	18.8	1	18.8
NE29 8RQ	Road	280	1	280.0
M26 4AF	Road	55.9	2	111.8
L3 4BE	Road	40.5	1	40.5
GL10 3TA	Road	206	15	3090.0
WA1 4RF	Road	24	2	48.0
S18 1DJ	Road	101	2	202.0
S9 3LX	Road	110	1	110.0
NG24 3EN	Road	173	3	519.0
TR14 OPJ	Road	524	1	524.0
LE11 5TF	Road	125	6	750.0
LE65 1DW	Road	111	1	111.0
CW7 3BS	Road	10.7	1	10.7
M23 9NF	Road	38.1	3	114.3
CW7 3AG	Road	11	5	55.0
WA1 4RF	Road	24	1	24.0
GU15 2PL	Road	321	2	642.0
WV11 1XR	Road	95.7	1	95.7
CW7 3PD	Road	11.4	3	34.2
YO18 7JA	Road	201	1	201.0
WV11 1XR	Road	95.7	6	574.2
WA7 1PT	Road	18.8	1	18.8
Canonsburg, USA	Road	661	1	661.0
	Ship	3310		3310
			Total Jan-Dec	*12 month Extrapolation*
		Road	*15 882.1*	*17 325.9*
		Ship	*3 810.0*	*4 156.4*

Table 40 Table of data for 'deliveries to site'

Turbine maintenance: The turbines at the studied plant have a major maintenance event planned every 10 years of life (Hepworth 2011). One major maintenance event was estimated by plant staff to equal approximately 80% of the work and hardware requirements of the original construction (Hepworth 2011). However in order to fall in line with the assumption adopted in the Severn Barrage study, the more conservative assumption of 100% of capital impact per maintenance event has been adopted. Hence, each turbine, steam and both gas, is assumed to have maintenance demand equivalent to 200% of appropriate turbine component inventory (inclusive of generator) during the plants 30 year lifetime. (The 80% estimate was adopted in the initial study, the results of which were presented at the SDEWES2012 conference and the accompanying journal paper is included in Appendix E).

8.4.3 DECOMMISSION AND DISPOSAL

No site specific data was available for the decommissioning of the case study CHP plant. However, because of the high value of the metals that make up the nearly all of the plant hardware, it is very likely that these parts will be reused or recycled. Recycling is typically of a higher environmental impact than reuse so, in accordance with the precautionary principle, it has been assumed that all steel and copper parts are recycled at the end of life. This disposal assumption is also applied to all turbine parts replaced at a maintenance event. The small amounts of other materials are assumed to be sent to landfill. The disposal scenario included in the scaled inventory entry for National Grid connection assumes that the non metal parts are incinerated (Burger and Bauer 2007).

8.5 LIFE CYCLE INVENTORY ANALYSIS FOR SEPARATE GENERATION SYSTEMS

8.5.1 HEAT ONLY SYSTEM FOR COMPARISON

The model developed to represent the hypothetical heat only alternative option for steam production was based on the EcoInvent database entry for 'steam, for chemical processes' (Zah 2007) but with the following UK specific edits:

Fuel: The full fuel demand is met by average UK natural gas supplied by the UK gas supply network. The original EcoInvent model assumed that the fuel consumed was 20% heavy fuel oil and 80% average European natural gas, by energy content.

Power: 1.1Wh of electricity is used per 1MJ of gas consumed. This power demand largely arises from the processes required to extract and purify the natural gas from crude oil (Jungbluth 2003). It is assumed that this power is supplied by the UK National Grid mix as modelled using data from DUKES 2008 (Hammond, Howard and Jones 2013). The original model assumed power was provided by an average European grid mix.

(N.B. The first iteration of the study, as presented at the SDEWES2012 conference, Appendix E, used a reference heat only system more similar to the original EcoInvent model, i.e. a fuel mix which was 80% UK natural gas and 20% heavy fuel oil and an average European grid power supply. The inventory refinement carried out for this updated and extended study was necessary because of the extra fuel use analysis. The improved inventory used here has a slightly reduced overall impact and hence the impact allocations to power generation, which are generated by subtracting the impact of the reference heat only system, are slightly increased. These improvements have resulted in very little alteration in the conclusions, bar the fact that the carbon saving with respect to the 1990 baseline National Grid has fallen from 81% to 77% which is slightly below rather than slightly above the UK reduction target.)

8.5.2 POWER ONLY SYSTEM FOR COMPARISON

The model developed to represent a UK gas fueled electricity only system is based on the EcoInvent database entry, 'electricity, natural gas, at power plant/GB U'(Heck 2003), with a appropriate edits to meet 2008 efficiency figures as published by DUKES, completed as part of the Transition Pathways work (Hammond, Howard and Jones 2013).

8.6 LIFE CYCLE INVENTORY ROBUSTNESS ASSESSMENT

In contrast to the Severn Barrage study, most of the inventory data was collected directly from manufacturing documentation rather than from other impact accounting studies. Hence, in order to test the robustness of the inventory, the initial results are compared to an existing data set in the EcoInvent database for a mini CHP system (Heck 2003), fuelled by a UK specific gas supply (Jungbluth 2003). Table 41 shows the characterised life cycle impact results for the case study CHP model and for the equivalent total life time heat output of the case study CHP, that is 73,584 GWh, generated the EcoInvent mini CHP model. The percentage difference between the two results is also given.

The large percentage differences in the categories of human toxity, freashwater eutrophication, terrestrial ecotoxity and freashwater ecotoxity can be traced to the fact that the case study CHP is assumed to be constructed using copper sourced from an average European mine whereas the EcoInvent Mini CHP uses copper sourced from an average mine in Latin America and the Caribbean. The differences are due to both the less environmentally conscious mining practices and the additional transportation required for the Latin American/Caribbean copper. It is fair to assume that the copper used in the case study CHP was mined in Europe, but this result does raise the question that if CHP implementation were to increase significantly in the UK, where would the materials come from and what would be the associated impact differences? This investigation is outside the scope of this research but it is noted in section 11.1.1.

The differences in the category of ionizing radiation are due to differences in upstream electricity use. The EcoInvent CHP inventory includes more metal parts, as also reflected in the category of metal depletion, and therefore more electrified machining in the construction stage. Also, that upstream electricity consumption is derived from an average UK National Grid technology mix in the case of the studied CHP whereas the EcoInvent CHP model uses an average European grid mix which includes a higher proportion of nuclear power, mostly from French plants. The discrepancy in water depletion is due to the 'open loop' water system currently in place at the case study CHP, as discussed in Section 8.1.

Impact category	Unit	Case Study CHP Model	EcoInvent Mini CHP plant for GB Gas (allocation heat)	Percentage difference
Climate change	t.CO_2eq	23 541 900.0	24 866 200.0	6%
Ozone depletion	t.CFC-11-eq	1.0	1.0	1%
Human toxicity	t.1,4-DB-eq	182 369.0	475 561.0	161%
Photochemical oxidant formation	t.NMVOC	15 834.8	18 580.0	17%
Particulate matter formation	t.PM10-eq	4 437.4	4 186.4	6%
Ionising radiation	t.U235-eq	65 511.4	139 744.0	113%
Terrestrial acidification	t.SO_2-eq	11 109.1	10 792.2	3%
Freshwater eutrophication	t.P-eq	141.6	332.0	134%
Marine eutrophication	t.N-eq	5 551.6	4 861.7	12%
Terrestrial ecotoxicity	t.1,4-DB-eq	60.5	107.7	78%
Freshwater ecotoxicity	t.1,4-DB-eq	3 613.1	7 917.8	119%
Marine ecotoxicity	t.1,4-DB-eq	26 265.4	30 165.3	15%
Agricultural land occupation	km^2	6.7	8.2	21%
Urban land occupation	km^2	16.1	15.8	2%
Natural land transformation	km^2	11.6	11.2	4%
Water depletion	km^3	0.2	0.0	96%
Metal depletion	t.Fe-eq	114 574.0	189 090.0	65%
Fossil depletion	t.oil-eq	10 213 100.0	9 895 380.0	3%

Table 41 Comparison of characterised results by impact category of the case study CHP with the equivalent lifetime heat load generated by a pre-existing EcoInvent model of a mini CHP (Heck 2003), fuelled by Great Britain specific gas supply (Jungbluth 2003), using Midpoint (H European) Analysis (to 1 decimal place)

Figure 60 compares the normalized impact scores of the two systems by category. The percentage difference between the normalized scores for each impact category will of course remain the same. However, normalizing the results enables the comparison of one impact category with another and thus provides one way to identify the most significant impact areas ('significant' being relative to the reference system used in the normalization).

In a normalized context, it can be seen that those categories where large differences where apparent in the characterised results are not critical to the overall impact. The impact score for natural land transformation is by far the most significant. This is almost entirely due to the methods used to extract and supply the fuel gas combusted over the plant's 30 year life time. There is only 4% difference between the two models in the category of natural land transformation, and this is almost entirely due to a 3% difference in total gas consumption, which is reflected in the results in the fossil depletion category. Such a close result in, what appears to be, the dominant impact category lends confidence that both models are acceptable representation from which to make estimates. The percentage difference is less than 25% in 11 out of 18 categories.

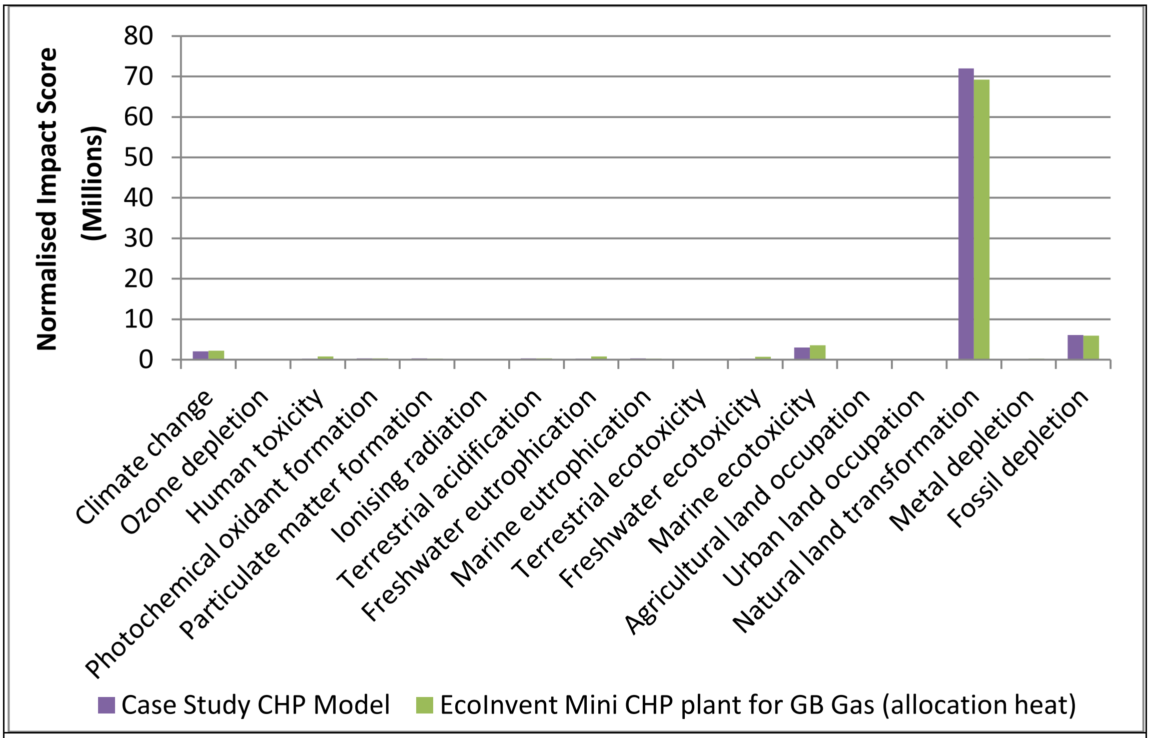

Figure 60 Comparison of normalised results by impact category of the case study CHP with the equivalent lifetime heat load generated by a pre-existing EcoInvent model of a mini CHP (Heck 2003), fuelled by Great Britain specific gas supply (Jungbluth 2003), using Midpoint (H European) Analysis

Figure 61 shows the same data as Figure 60 but summed so that the two systems can be more easily compared by their total normalized impact score, or environmental burden. The total normalized impact scores for the case study model and the equivalent EcoInvent model are 85.4 million and 84.9 million respectively. Overall, the percentage difference between the total normalized impact scores or 'total impact score' is only 1%.

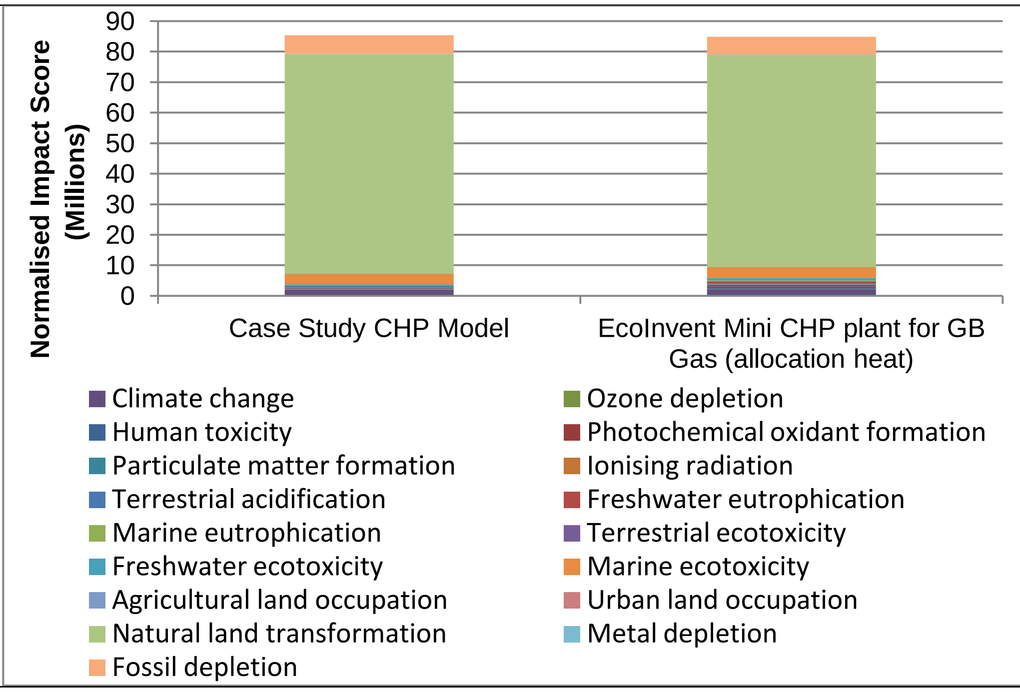

Figure 61 Comparison of normalised results by system of the case study CHP with the equivalent lifetime heat load generated by a pre-existing EcoInvent model of a mini CHP (Heck 2003), fuelled by Great Britain specific gas supply (Jungbluth 2003), using Midpoint (H European) Analysis

However, the category of natural land transformation also has one of the least well developed assessment methods within ReCiPe and so results in this category should be reviewed with particular caution, especially when it is the dominant impact. Figure 62 shows the same information as Figure 60 but with the result for natural land transformation removed so that the other results can be seen more clearly. The differences in human toxity and freashwater ecotoxicity and eutrophication can be seen more obviously here, but the normalized impact scores in these categories still fall well below that of climate change, marine eutrophication and fossil fuel depletion, which have percentage variations of 15% or less.

This analysis may exhibit one of the flaws of using a single score approach; even though the two representations vary significantly in 7 out 18 impact categories (over 100% in four categories and over 50% in a further three) because these impacts have a small contribution in a normalized context it seems reasonable to dismiss them. If the impacts of the 'normal' reference system were sufficiently different such that these seven categories dominated, then a completely different conclusion might be reached. These results show the importance of also always considering the characterised results and, hence, be aware of the reasons for the differences, even if the normalized results suggest that a further iteration of the LCI is unwarranted.

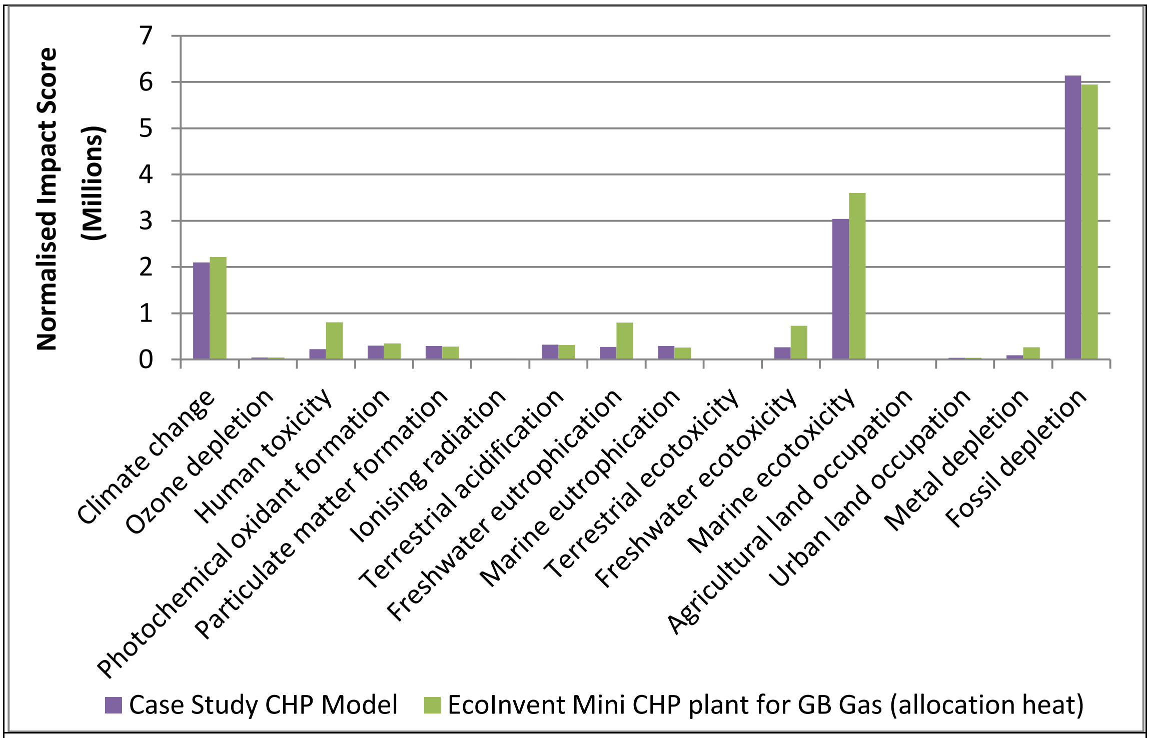

Figure 62 Comparison of normalised results by impact category excluding natural land transformation of the case study CHP with the equivalent lifetime heat load generated by a pre-existing EcoInvent model of a mini CHP (Heck 2003), fuelled by Great Britain specific gas supply (Jungbluth 2003), using Midpoint (H European) Analysis

Figure 63 compares the total lifetime energy demand of the case study model with that of the EcoInvent reference model (Heck 2003). The EcoInvent representation is around 3% less energy intensive than the case study model but this is minimal and is explained by an almost identical percentage difference in the gas consumption.

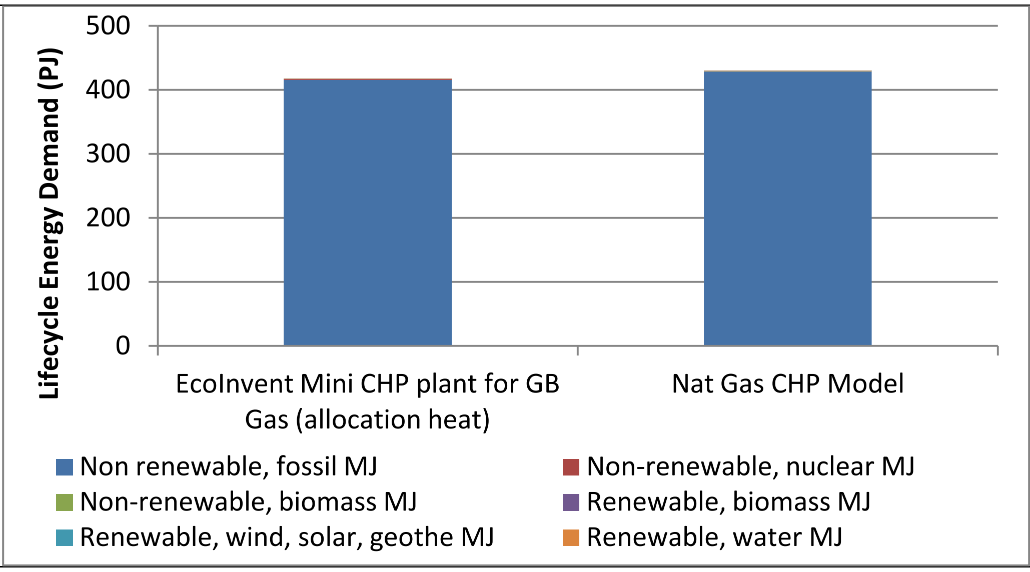

Figure 63 Model comparison by energy demand

As already shown in Table 41 in the category climate change, the difference in GWP potential between the two systems is 6%. This difference is due almost entirely due to operational emissions, the case study model is site specific data and the EcoInvent representation is averaged data for total Swiss CHP emissions. A difference of this magnitude is well within expected limits.

8.7 LIFE CYCLE IMPACT ASSESSMENT RESULTS INTERPRETATION

Table 42 splits the characterized impact scores for the case study CHP into the four life cycle stages of construction, operation, maintenance and disposal. The operation stage is clearly, and perhaps unsurprisingly, the biggest contributing life stage in every one of the impact categories assessed. This is largely because the resource use and emissions associated with the extraction and combustion of the CHP's lifetime gas consumption far outweigh that which is associated with any other inventory entry.

Impact category	Unit	Construction	Operation	Maintenance	Disposal
Climate change	t.CO_2eq	16 251.4	23 514 400.0	5 836.8	5 473.2
Ozone depletion	t.CFC-11-eq	0.0	0.9	0.0	0.0
Human toxicity	t.1,4-DB-eq	16 170.4	101 296.0	13 035.4	51 866.7
Photochemical oxidant formation	t.NMVOC	54.2	15 704.0	22.1	54.5
Particulate matter formation	t.PM10-eq	49.5	4 310.4	19.3	58.2
Ionising radiation	t.U235-eq	4 158.1	57 130.3	1 596.5	2 626.4
Terrestrial acidification	t.SO_2-eq	125.2	10 869.0	30.2	84.7
Freshwater eutrophication	t.P-eq	11.6	91.6	8.3	30.1
Marine eutrophication	t.N-eq	18.8	5 507.4	7.4	18.0
Terrestrial ecotoxicity	t.1,4-DB-eq	2.9	53.3	1.1	3.1
Freshwater ecotoxicity	t.1,4-DB-eq	270.6	2 421.3	202.2	719.0
Marine ecotoxicity	t.1,4-DB-eq	296.8	24970.6	217.6	780.4
Agricultural land occupation	km^2	0.5	5.8	0.1	0.3
Urban land occupation	km^2	0.3	15.5	0.1	0.2
Natural land transformation	km^2	0.0	11.6	0.0	0.0
Water depletion	km^3	0.0	0.2	0.0	0.0
Metal depletion	t.Fe-eq	12 971.8	40 138.3	11 356.6	50 107.7
Fossil depletion	t.oil-eq	5 154.2	10 202 500.0	1 859.9	3 634.0

Table 42 Characterised results by impact category of the life cycle stages of the case study CHP, using Midpoint (H European) Analysis (to 1 decimal place)

As already stated in Section 8.6, the lifetime normalised score for the CHP unit is 85.4 million. Assuming a 30 year lifespan, the emission rate of the unit is approximately quivalent to that of 2.8 million average European citizens, which is roughly the population of Rome. Figure 64 shows the normalized impact scores for each impact category and the contribution from each life stage. Figure 65 shows the same data but summed so that the total impact per life stage can be more easily compared. Both figures also show that the operation stage dominates the overall impact of the CHP life cycle and the operational impact is, in a normalized context, dominated by the category of natural land transformation. As already discussed, this is almost entirely due to the plant's gas demand.

As was the case in the assessment of the Severn Barrage, the identification of the operational stage of life as the dominant stage means that the lifetime impact estimate is proportional to the assumed design life (except for unrealistically low assumptions). This makes the design lifetime a key sensitivity to the total impact estimate but the rate of impact, e.g. annual impact or impact per unit of power generated, would be unaffected.

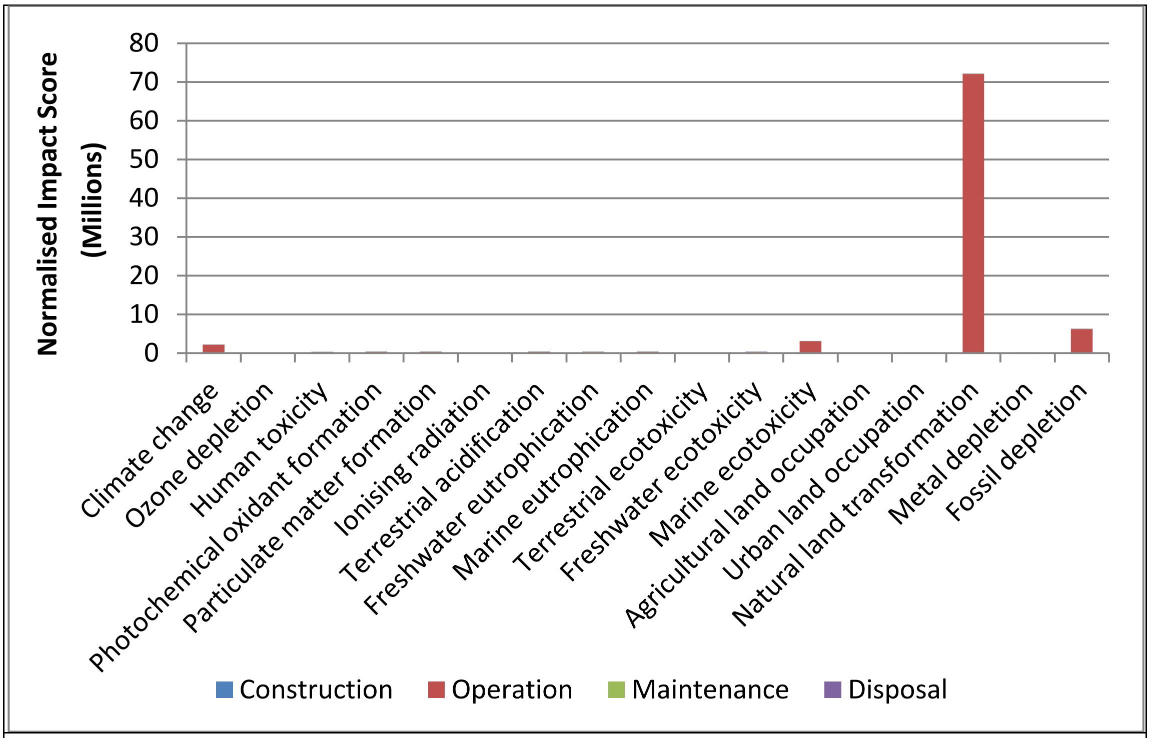

Figure 64 Normalised results by impact category for each life stage of the case study CHP (Winnington), using Midpoint (H European) Analysis

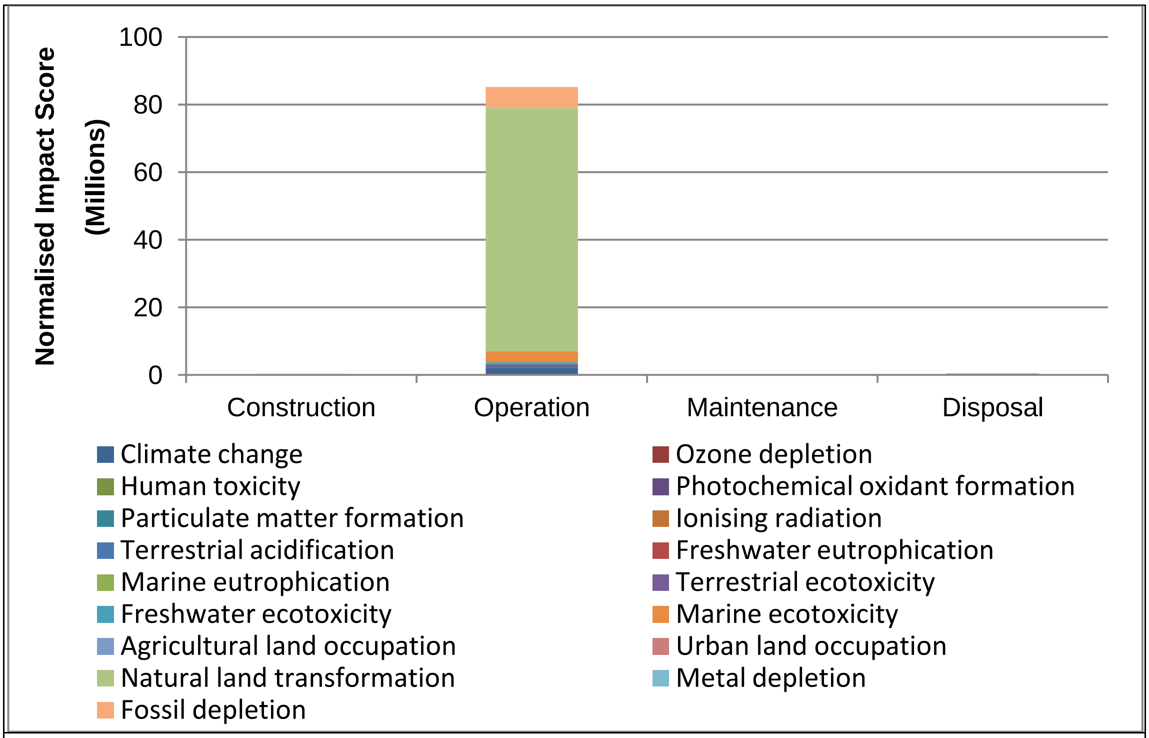

Figure 65 Normalised results by life stage for each impact category for the case study CHP (Winnington), using Midpoint (H European) Analysis

As already mentioned, the method for calculating natural land transformation is not as well developed as some of those for the other categories, hence it is worth considering the results outside the shadow of that cast by that large result. Figure 66 shows the same results as Figure 64 but with the natural land transformation removed. It is still apparent that the operational stage is the most impactful.

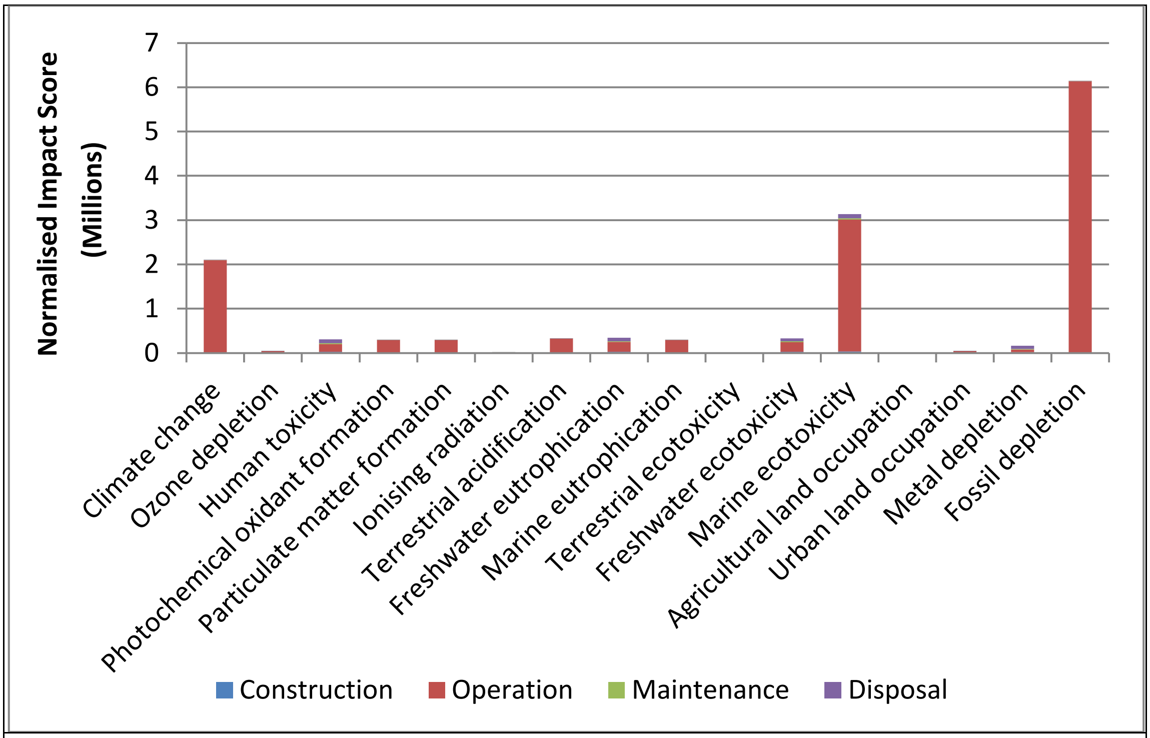

Figure 66 Normalised results by impact category excluding natural land transformation for each life stage of the case study CHP (Winnington), using Midpoint (H European) Analysis

8.7.1 OPERATION ENVIRONMENTAL IMPACT RESULTS IN DETAIL

Table 43 gives the characterised impact results for the operation stage by each inventory entry. The impacts from either emissions and waste or from fuel use dominate or both, dominate the overall impact in every category. As most of the impacts in emissions and waste are caused by the combustion of the fuel, these results confirm that the gas consumption is the most impactful activity over the whole CHP lifetime.

Impact category	Unit	Lubrication Oil	Emissions and Waste	Fuel, Natural Gas	Tap water	Deliveries to Site
Climate change	kg.CO_2eq	5 285 655	22 570 125 000	845 647 890	41 395 848	51 906 483
Ozone depletion	kg.CFC-11-eq	5	0	930	2	7
Human toxicity	kg.1,4-DB-eq	1 172 286	0	67 921 791	29 989 583	2 212 661
Photochemical oxidant formation	kg.NMVOC	37 042	11 036 578	3 594 422	110 795	925 207
Particulate matter formation	kg.PM10-eq	15 464	2 828 400	1 030 013	63 416	373 117
Ionising radiation	kg.U235-eq	648 585	0	29 738 278	25 716 444	1 027 027
Terrestrial acidification	kg.SO_2-eq	56 203	7 157 700	2 284 159	163 686	1 207 206
Freshwater eutrophication	kg.P-eq	909	0	56 494	32 741	1 419
Marine eutrophication	kg.N-eq	7 345	4 102 005	1 046 128	38 468	313 412
Terrestrial ecotoxicity	kg.1,4-DB-eq	2 982	0	37 351	8 140	4 874
Freshwater ecotoxicity	kg.1,4-DB-eq	31 457	0	1 528 884	815 478	45 438
Marine ecotoxicity	kg.1,4-DB-eq	35 634	0	24 121 238	603 650	210 041
Agricultural land occupation	m^2	15 631	0	2 941 704	2 855 040	27 319
Urban land occupation	m^2	52 097	0	13 391 177	1 947 685	78 613
Natural land transformation	m^2	19 927	0	11 558 464	13 718	26 053
Water depletion	m^3	45 975	0	3 136 955	147 600 303	62 612
Metal depletion	kg.Fe-eq	124 542	0	37 346 115	2 479 772	187 887
Fossil depletion	kg.oil-eq	13 845 647	0	10 159 579 800	11 005 219	18 069 562

Table 43 Characterised results by impact category of the operational activities of the case study CHP, using Midpoint (H European) Analysis (to 6 significant figures)

Figure 67 shows the normalized results for the operation stage by inventory entry. It confirms that the large impact in the category of natural land transformation is due to the gas demand, as already discussed. It is interesting to note that the normalized score for natural land transformation is considerably higher than that of climate change. This implies that the extraction of the natural gas burnt at the case study CHP is considerably more natural land use intensive than the average combusted fossil fuel in the reference system, i.e. Europe. This is because the natural gas network in the UK is assumed to be predominately fed by off shore gas wells (Jungbluth 2003) which are assumed to have a greater direct land use footprint on virgin land, specifically the sea bed, than on shore fossil fuel extraction systems which dominate the average European supply.

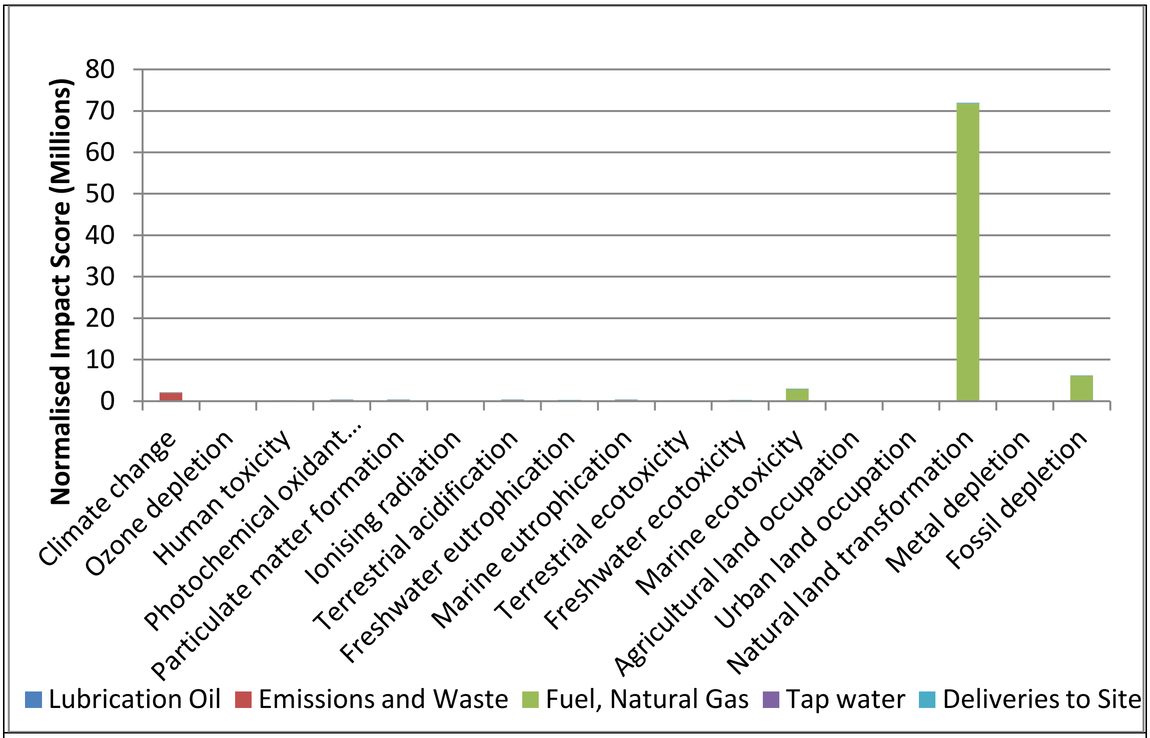

Figure 67 Normalised results by impact category for the operational activities of the case study CHP (Winnington), using Midpoint (H European) Analysis

Figure 68 shows the impact contribution from each inventory to the total operational impact in each category, but with natural land transformation removed so that the remaining categories can be seen more clearly. The large scores in the categories of fossil fuel depletion, marine ecotoxicity and climate change further confirm that the natural gas consumption is the dominate contributor to the plants overall lifetime impact. The fact that the fossil fuel impact score exceeds that of the climate change score is to be expected as natural gas is one of the lowest carbon fossil fuels.

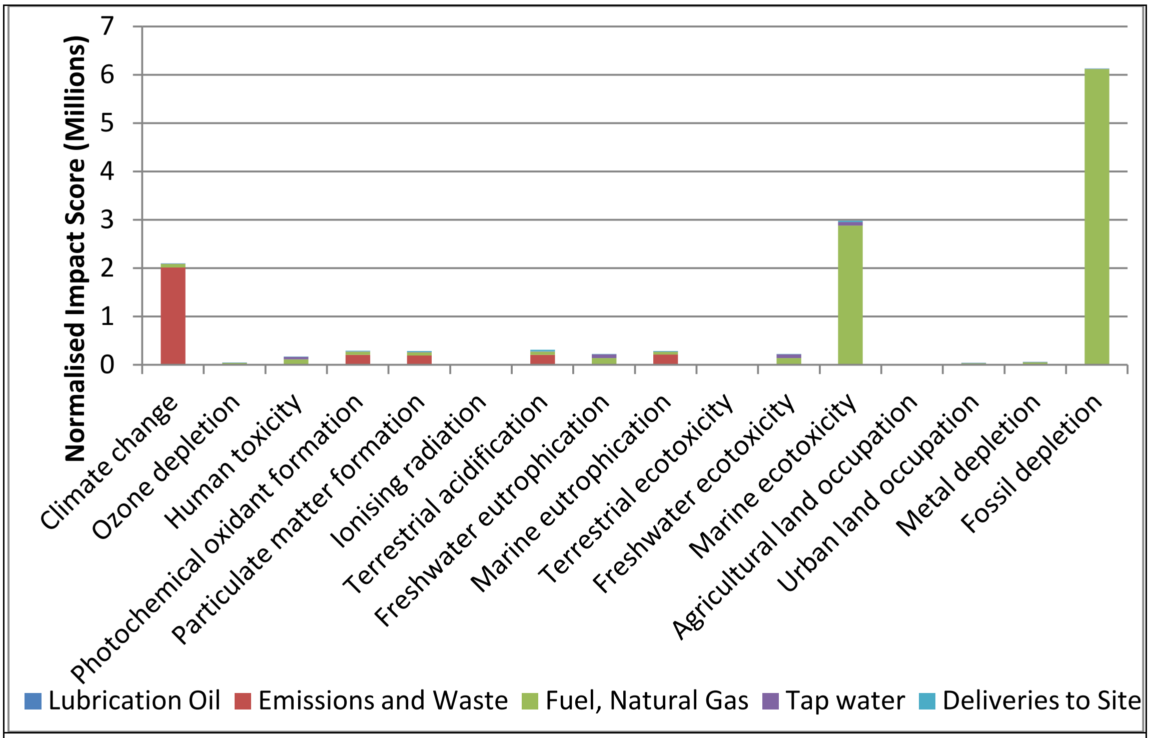

Figure 68 Normalised results by impact category excluding natural land transformation for the operational activities of the case study CHP (Winnington), using Midpoint (H European) Analysis

8.7.1.1 Sensitivity Testing

The 'annual deliveries to site' was the inventory entry for which least satisfactory data was available and, hence, large general assumptions were made. These results show that the impact of the annual deliveries to site actually contributes less than 3% of the total operational impact in 12 out of 18 environmental impact categories, and less than 1% in 7 out of 18 categories. However, the contribution exceeds 6% in three categories; that is 9% of particulate matter formation, 11% terrestrial acidification and 9% terrestrial ecotoxicity. These are all categories that would be associated with diesel powered road transportation.

Figure 67 shows that the categories where the impact from site deliveries exceed 6% have a limited significance in the normalized context. For this study, further analysis of this inventory entry is unwarranted. However, this may well be necessary if the impact of the major operational activities, i.e. gas consumption, were reduced or if the reference system for normalization changed.

8.7.2 CARBON ANALYSIS

Table 41 shows that the life time carbon emissions, and therefore GWP, of the case study CHP is 23.54 Mt.CO_2 (equivalent) (to 4 significant figures). Table 42 shows that nearly all of these emissions, that is 23.51 Mt.CO_2 (equivalent) (to 4 significant figures), occur during the operation phase of life. These emissions, as might be expected, are caused by the combustion of the natural gas demand over the plants lifetime. The normalized impact scores for climate change, as shown in Figure 64 and Figure 65, however show that this is not a very significant impact in comparison to fossil fuel depletion, in a European context, which is consistent with the fact that the natural gas is considered the lowest carbon intense fossil fuel.

8.7.3 ENERGY ANALYSIS

Table 44 splits the characterized energy demands for the case study CHP into the four life cycle stages of construction, operation, maintenance and disposal. As would be expected given the impact results, the operation stage is the biggest contributing life stage in every one of the energy resource categories considered by the analysis and, hence, to the overall system energy demand. This is, of course, because of the CHP's lifetime gas consumption.

The energy demand from renewable natural processes are shown in the table for completeness, however these contributions will not be included in any subsequent energy analysis in line with the approach adopted for the Severn Barrage study. A total energy demand figure of 429,564 TJ to the nearest TJ will be used hence forth.

Impact category	Unit	Construction	Operation	Maintenance	Disposal
Non renewable, fossil	GJ	216 698	428 462 582	78 098	74 493
Non-renewable, nuclear	GJ	42 937	588 422	16 243	10 490
Non-renewable, biomass	GJ	4	268	0	0
Renewable, biomass	GJ	2 872	69 667	920	782
Renewable, wind, solar, geothermal	*GJ*	*622*	*9 612*	*297*	*190*
Renewable, water	*GJ*	*14 773*	*78 487*	*3 434*	*5 072*

Table 44 Lifetime energy demand per energy resource category by life stage for the case study CHP (to the nearest GJ)

Figure 69 compares the energy demand for each life stage of the case study CHP for the four energy resource categories which will be included in subsequent analysis. It can be seen that the operation energy demand vastly dominates that of the other life stages and that the operational demand is dominated by the energy demand for fossil fuels i.e. the lifetime gas consumption, which confirms what has already been deduced from the environmental impact analysis.

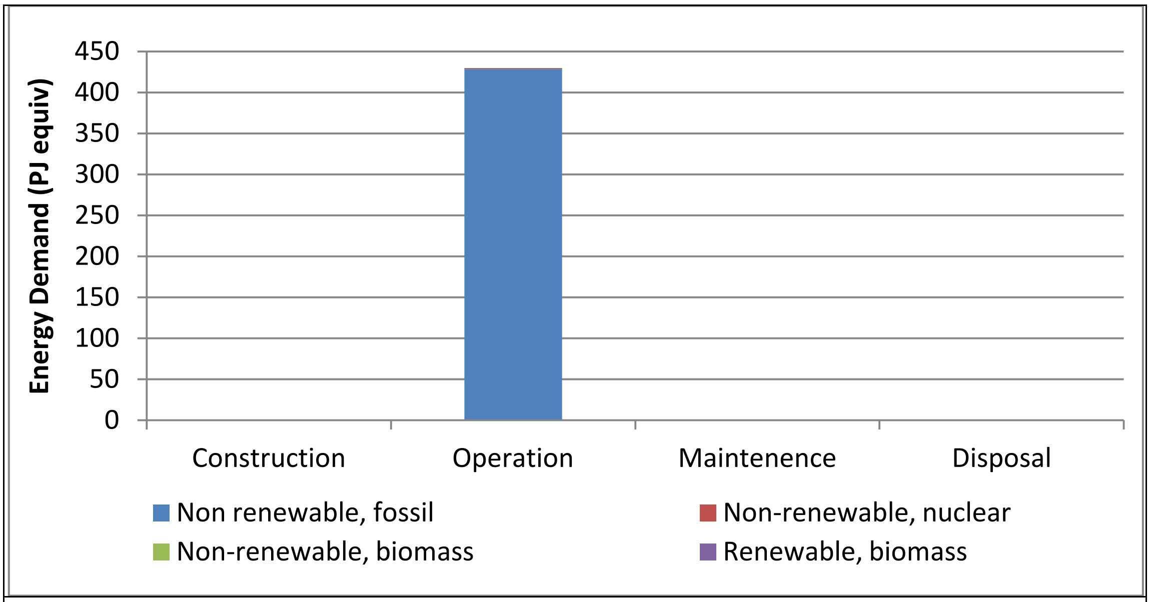

Figure 69 Lifetime energy demand by life stage for each impact category for the case study CHP

8.7.3.1 Energy Gain Ratio

As already stated the lifetime heat and power generation of the studied CHP plant is 73,584 GWh(th) and 27,331 GWh(e) respectively, which is equivalent to 264,902 TJ and 98,392 TJ. Hence the energy gain ratio, EGR. of the case study CHP is 0.8. This value is less than 1 demonstrating that the system demands more energy than it generates, which is to be expected as the energy demand is inclusive of fuel. A fossil fuelled power generation system cannot deliver more energy than it consumes as this would defy the second law of thermodynamics. For comparison, the gas fuelled power and steam only systems have estimated EGRs of 0.5 and 0.8 respectively.

Typical fuel efficiencies would not exceed 0.6 for a combined cycle gas turbine (Robb 2010) and would be around 0.75 for an industrial boiler system (Van Wortswinkel and Nijs 2010), which both fall below the estimated EGR for the case study CHP. These values are based only on fuel consumption rather than full life cycle energy demand so comparable numbers are actually likely to be a bit lower.

The reported overall fuel efficiencies for average UK gas turbine and combined cycle CHPs are 0.71 and 0.66 respectively. Again, is only based on fuel efficiency. However it indicates that the case study CHP performs well compared to the current technology stock, despite its limited power capacity.

8.7.3.2 Energy Payback Period

The annual total energy output is equal to the sum of the annual heat and power output, giving a result of 3,363 GWh which is equivalent to 12,110 TJ. Hence the system payback period of just over 35 years can be calculated, which is longer than the plants lifespan. This is also to be expected, as it is also thermodynamically impossible for a fossil fuelled power generator to payback within its lifetime if fuel demand is included in the total energy demand estimate. For comparison, when it is assumed that the models for gas fuelled power and heat only systems generate the same lifetime energy at the same equivalent annual rate, they have energy payback periods of 58 years and 36 years respectively.

The EGR and energy payback period estimates suggest that the case study CHP provides little improvement over steam only production, implying that the energy benefits are to be found with respect to the power generation. This synergizes with the study assumption that the CHP technology is installed only order to exploit the heat demand for the generation of low impact electricity.

8.8 SAVINGS COMPARED TO SEPARATE GENERATION

These impact estimates for the case study CHP can be used to quantify the environmental impact savings made compared to separate heat and power generation. Table 45 gives the characterised impact results for the equivalent lifetime heat and power generation of the case study CHP generated by separate natural gas fuelled systems, see Section 8.5, specifically 27,331 GWh(e) of power and 73,584 GWh(th) of steam. Most importantly, the table also shows the impact saving achieved by the case study CHP, per category, over its lifetime compared to separate generation. This is calculated using:

$$\begin{aligned}&(Impact\ of\ Natural\ Gas\ Fuelled\ Power\ Generation\\ &\qquad + Impact\ of\ Natural\ Gas\ Fuelled\ Steam\ Generation)\\ &\qquad - Lifetime\ impact\ of\ Case\ Study\ CHP\\ &\qquad = Case\ Study\ CHP\ Lifetime\ Saving\end{aligned}$$

The only impact category where the sum impact of generation from separate systems is less than that of the case study CHP is metal depletion. This is likely to be because the results for the separate systems do not represent a whole plant lifetime. Each of these separate generation models assumes a higher lifetime output than this comparison requires, hence only a fraction of the plant hardware would be allocated, whereas in the assessment of the case study CHP, the whole plant is, of course, included.

Impact category	Unit	Natural Gas Fuelled Power Generation (27 331 GWh(e))	Natural Gas Fuelled Steam Generation (73 584 GWh(th))	Case Study CHP Lifetime Saving (30yrs)
Climate change	kg.CO_2eq	11 034 600 000	18 529 300 000	6 021 940 000
Ozone depletion	kg.CFC-11-eq	413	700	168
Human toxicity	kg.1,4-DB-eq	46 871 900	247 883 000	112 386 000
Photochemical oxidant formation	kg.NMVOC	11 660 700	9 455 880	5 281 730
Particulate matter formation	kg.PM10-eq	2 672 210	2 460 230	695 043
Ionising radiation	kg.U235-eq	14 022 500	209 053 000	157 564 000
Terrestrial acidification	kg.SO_2-eq	6 448 730	6 069 010	1 408 690
Freshwater eutrophication	kg.P-eq	31 627	287 490	177 539
Marine eutrophication	kg.N-eq	4 154 500	3 184 750	1 787 670
Terrestrial ecotoxicity	kg.1,4-DB-eq	20 345	63 028	22 893
Freshwater ecotoxicity	kg.1,4-DB-eq	940 622	5 081 320	2 408 870
Marine ecotoxicity	kg.1,4-DB-eq	11 001 100	21 631 200	6 366 910
Agricultural land occupation	m^2	1 396 490	7 719 510	2 384 300
Urban land occupation	m^2	6 921 780	12 277 000	3 145 390
Natural land transformation	m^2	5 146 990	8 581 400	2 102 970
Water depletion	m^3	41 626 000	125 955 000	16 335 800
Metal depletion	kg.Fe-eq	20 587 000	45 669 900	-48 317 500
Fossil depletion	kg.oil-eq	4 515 490 000	7 584 250 000	1 886 590 000

Table 45 Characterised results by impact category of separate natural gas fuelled generation of the equivalent lifetime energy load of the case study CHP, using Midpoint (H European) Analysis (to 6 significant figures)

Figure 70 compares the total normalized impact score, or environmental burden, for the life cycle of the case study CHP with that of the separate heat and power models. The CHP system has a higher overall impact than that of the heat only system but a lower impact than if the total lifetime heat and power were generated by separate systems.

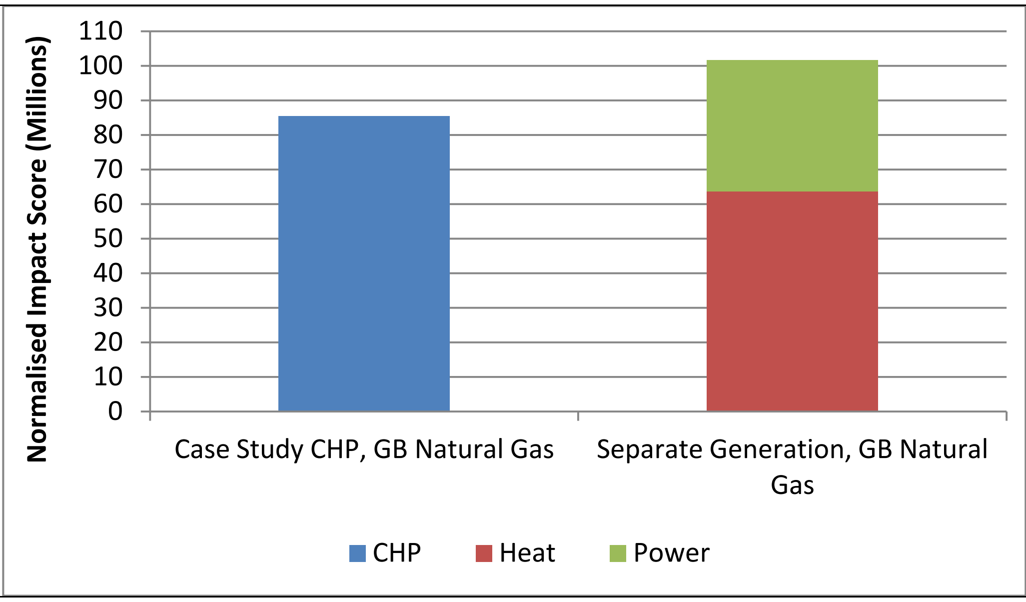

Figure 70 Comparison of total normalised impact score for the case study CHP with the equivalent amount of life time heat and power generated using separate gas fired technologies , using Midpoint (H European) Analysis

Table 46 provides the information required to calculate the total impact savings as estimated in comparison to the separate generation models. It can be seen that the case study CHP has a total normalized impact saving, or reduced environmental burden, of around 16% when compared to separate energy generators.

	Annual Total Normalised Impact Score	Lifetime Total Normalised Impact Score
Separate natural gas fired electricity production	1 267 000	38 010 000
Separate natural gas fired steam production	2 123 000	63 680 000
Case study CHP	2 848 000	85 430 000
Impact savings	542 100	16 260 000

Table 46 Information required to calculate case study CHP impact improvements over separate energy generation, using Midpoint (H European) Analysis (4.s.f.s)

8.8.1.1 Displaced Environmental Impact Payback Compared to Separate Generation

The displaced environmental impact period is the operational time after which the impact savings offset the overall impact of the system. It can be seen from the data in Table 46 that the lifetime savings are less than a fifth of the overall impact, hence it would take more than 150 years for the system savings to offset the CHP's overall impact.

The exact displaced impact period is given by:

$$\frac{Life\ Cycle\ Impact\ for\ Case\ Study\ CHP}{Annual\ Impact\ Saving\ Compared\ to\ Separate\ Heat\ and\ Power\ Generation} = 158\ years$$

However, these calculations do not tell the story within the specific context of this case study, i.e. the feasibility of exploiting an existing heat load for the generation of low impact power.

8.8.2 CARBON ANALYSIS

Table 45 shows that over the lifetime of the case study CHP, a saving of 6.021 Mt.CO_2 (equivalent) (to 4 significant figures), is available in comparison to the equivalent lifetime heat and power outputs generated by separate heat and power technologies. This gives a GWP saving of 20% in comparison to separate energy generators. The annual saving would be 0.201 Mt.CO_2 (equivalent) (to 4 significant figures) so the displaced carbon payback period would be 117 years.

8.8.3 ENERGY ANALYSIS

Table 47 provides the information required to calculate the energy savings for the studied CHP scheme as against the separate generation models. The case study CHP delivers a total energy saving of around 16% when compared to the separated generation models. If it is assumed that the case study CHP system displaces these alternative separate heat and power generation systems than the energy savings would offset the total energy demand of the case study CHP in just less than 160 years, i.e. the displaced energy payback period against separate gas fuelled energy generation is 160 yrs.

	Annual Energy Demand, TJ	**Lifetime Energy Demand, TJ**
Separate natural gas fired electricity production (Heck 2003)	6 327	189 816
Separate natural gas fired steam production (Zah 2007)	10 676	320 290
Case study CHP	14 323	429 677
Impact savings	2 684	80 516

Table 47 Information required to calculate case study CHP energy demand improvements over separate energy generation (to nearest TJ)

8.9 LIFE CYCLE ASSESSMENT RESULTS INTERPRETATION: POWER (ONLY) IN CONTEXT

To investigate the impact per unit of power generated, the total normalized impact score, or environmental burden, for the case study CHP must be allocated between the heat and power generated according to the three methods proposed in 8.3.2. The 'fixed heat' allocation method yields the lowest impact allocation to power generation, whereas the DUKES allocation method yields the highest, giving total normalized impact scores of 21,040,000 and 36,410,000 respectively, to 4 significant figures. This is to be expected as the DUKES method necessarily discounts the heat production. The 'percentage' allocation, of 31,710,000 to 4 significant figures, falls between the two others, so is not included in any further analysis as the two extremes are sufficient to represent the potential variation. Figure 71 visualizes the different proportional allocations that different methods yield for the total normalized impact score.

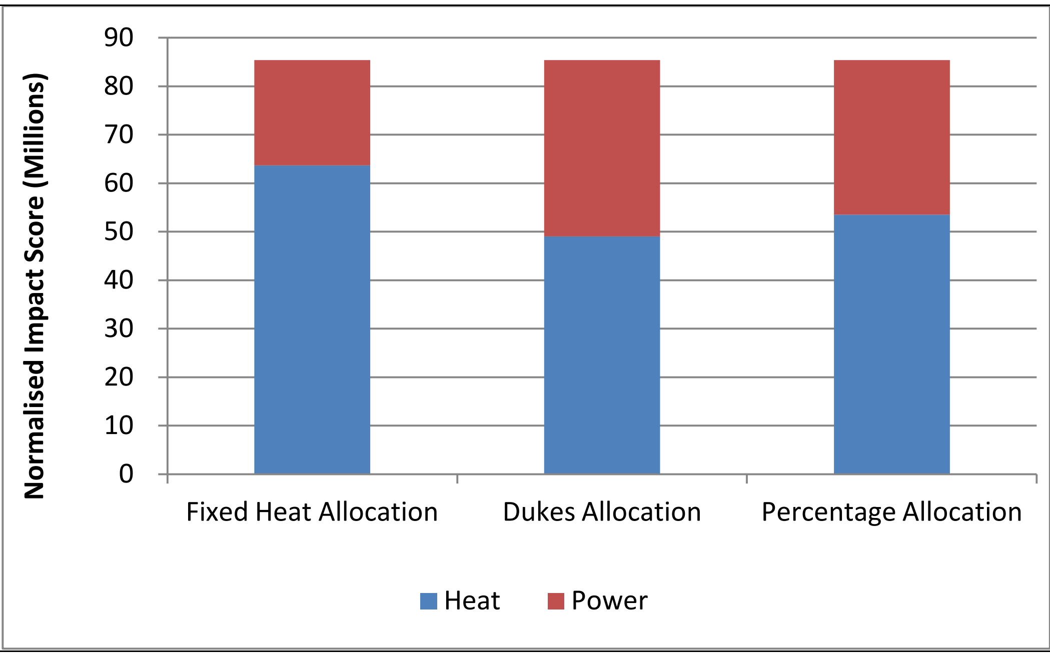

Figure 71 Comparison of allocation method results using total normalised impact score, using Midpoint (H European) Analysis

The power allocation only was calculated for the characterized and normalized results for each impact. Then, each impact result was divided by the total estimated lifetime power generation of the plant, that is 27,331 GWh(e), to generate an impact per 1MWh generated or a 'specific' impact result. Although it is not expressly done so here, these can be compared to the specific characterised results for the five National Grid datasets taken from the Transition Pathways Whole Systems (Hammond, Howard and Jones 2013) work which are presented in section3.6.3.2.

The specific characterized results per impact category for the case study CHP are given in Table 48. In 3 out of 18 categories, the impact estimated for the heat only system actually exceeds that of the case study CHP for the same heat output, hence when the 'fixed heat' allocation method is applied the power generated actually has a negative characterized result. These impacts cannot, therefore be associated with the fuel demand. They are mostly associated with the operational power demand which in the case of the heat only system is met by the National Grid, which includes a range of generating technologies, and in the case of the studied CHP is met by the plant itself, and hence only one technology type. Some of the difference is also due to the inevitable variation in the LCI for the systems' construction. However, two of these negative scores are nil when corrected to the nearest whole unit and positive scores are generated for the four categories already identified by the normalization as most significant: that of natural land transformation, fossil fuel depletion, marine ecotoxicity and climate change, which are categories to which the greatest contribution is likely to come from the natural gas consumption. The results for natural land transformation and marine ecotoxicity are in fact, also nil when corrected to the nearest unit.

Impact category	Unit	Case Study CHP, Fixed Heat Allocation	Case Study CHP, DUKES Allocation
Climate change	kg.CO_2eq/MWh(e)	183	367
Ozone depletion	kg.CFC-11-eq/MWh(e)	0	0
Human toxicity	kg.1,4-DB-eq/MWh(e)	1	3
Photochemical oxidant formation	kg.NMVOC/MWh(e)	0	0
Particulate matter formation	kg.PM10-eq/MWh(e)	0	0
Ionising radiation	kg.U235-eq/MWh(e)	-2	1
Terrestrial acidification	kg.SO_2-eq/MWh(e)	0	0
Freshwater eutrophication	kg.P-eq/MWh(e)	0	0
Marine eutrophication	kg.N-eq/MWh(e)	0	0
Terrestrial ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0
Freshwater ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0
Marine ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0
Agricultural land occupation	m^2/MWh(e)	0	0
Urban land occupation	m^2/MWh(e)	0	0
Natural land transformation	m^2/MWh(e)	0	0
Water depletion	m^3/MWh(e)	1	2
Metal depletion	kg.Fe-eq/MWh(e)	3	2
Fossil depletion	kg.oil-eq/MWh(e)	96	159

Table 48 Specific characterised results by impact category for the power generated b the case study CHP, using Midpoint (H European) Analysis (to the nearest whole unit)

The specific normalized scores for power were then summed to provide a total impact score, or environmental burden. Figure 72 shows that the total normalized impact per power unit generated by the case study CHP is less than that of the reference gas fuelled power only system, irrespective of which method is used to allocate the impact of the power generated, although when the DUKES allocation method is adopted, the specific impact of the two systems are almost equivalent. This is an encouraging result in favour of CHP systems, as it demonstrates that even in a heat lead system where the turbines are running below capacity, CHP systems have the potential to generate power with a lower overall environmental impact than a power only system using the same fuel type.

Hence, it can be postulated that any CHP system where the heat to power ratio was more balanced, even greater savings compared to power only systems could be seen. N.B In systems where the demand for heat and power are more balanced, the 'fixed heat' allocation is unlikely to be appropriate and the DUKES method alone should be adopted.

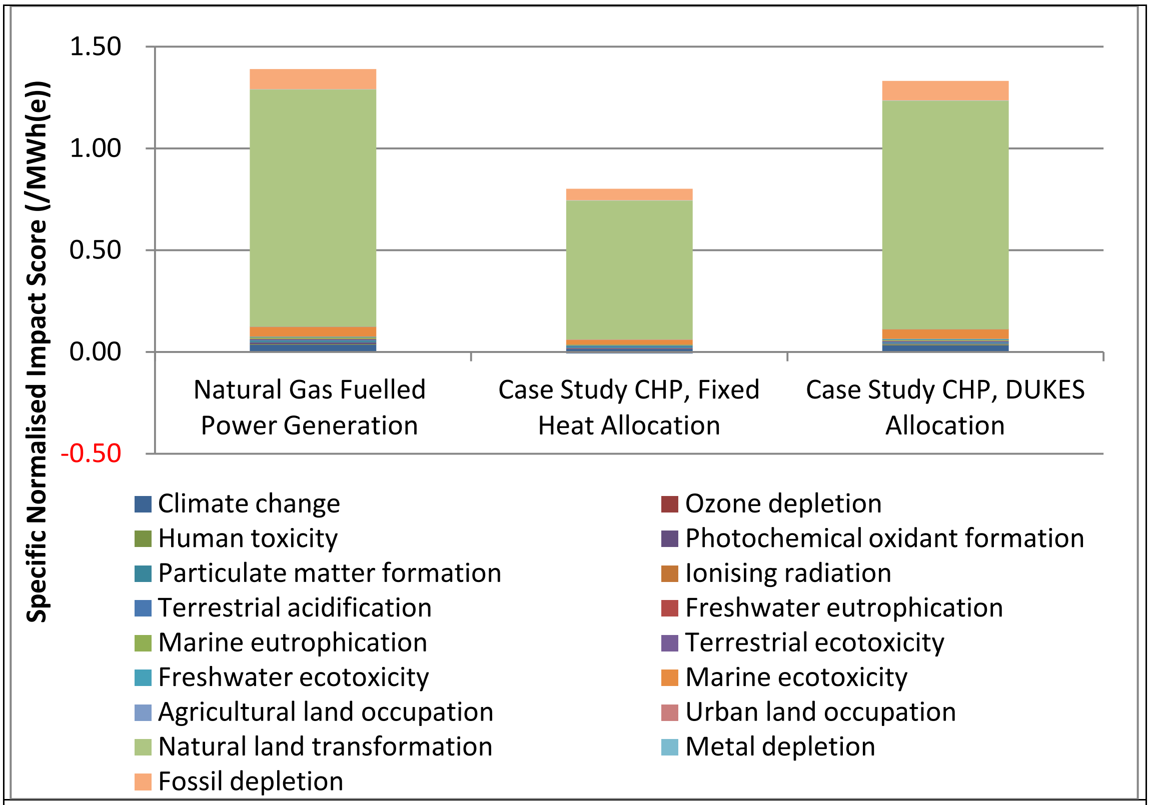

Figure 72 Comparison of specific normalised scores for by power generation system for gas fuelled systems only, using Midpoint (H European) Analysis

However, the power generated by the case study CHP is fed into the Grid mix rather than directly displacing other gas fuelled power generation, hence it is more appropriate to compare the specific impact of the CHP plant with that of representations of the UK National Grid. Figure 73 compares this specific total impact score to that of models of the UK National Grid mixes taken from the Transition Pathways Whole Systems work (Hammond, Howard and Jones 2013). It can be seen that the case study CHP has a higher normalized score in the category of natural land transformation in comparison to the National Grid models, which have a more even spread across the full suite of impact categories. This is again due to the assumption that the case study CHP is fuelled by off shore gas. Even the fossil fuelled technologies that contribute to the Grid mixes, and are dominant in the 1990 baseline model, are largely coal based, which would be mined on shore and necessarily have a smaller virgin land footprint. However, overall the specific impact of the power generated by the case study CHP is clearly lower than both the 1990 baseline and the 2008 National Grids, irrespective of what allocation method is adopted. Importantly, when the 'fixed heat' allocation method is adopted, the case study CHP also has a lower impact per unit generated than all three of the 2050 Grid mixes based on the Transition Pathways scenarios. When the DUKES allocation method is applied, the impact exceeds that of the Central Control and Thousand Flowers 2050 Grid mixes. (It is important to remember, however, that the higher impact allocation to power using the DUKES method does imply a discount for the heat so there is, necessarily, the same impact reduction overall.) The specific impact of the Market Rules 2050 Grid mix, however, exceeds that of the case study CHP, irrespective of allocation method. It is also important to note that the specific impact of the Market Rules 2050 Grid mix exceeds that of the natural gas fuelled power only system as depicted in Figure 72. This is because of the high proportion of fossil fuelled technologies with carbon capture and storage, CCS, included in this pathway's technology mix. This result begins to highlight the environmental impacts of fossil fuel combustion that remain even when carbon emissions are, seemingly, addressed.

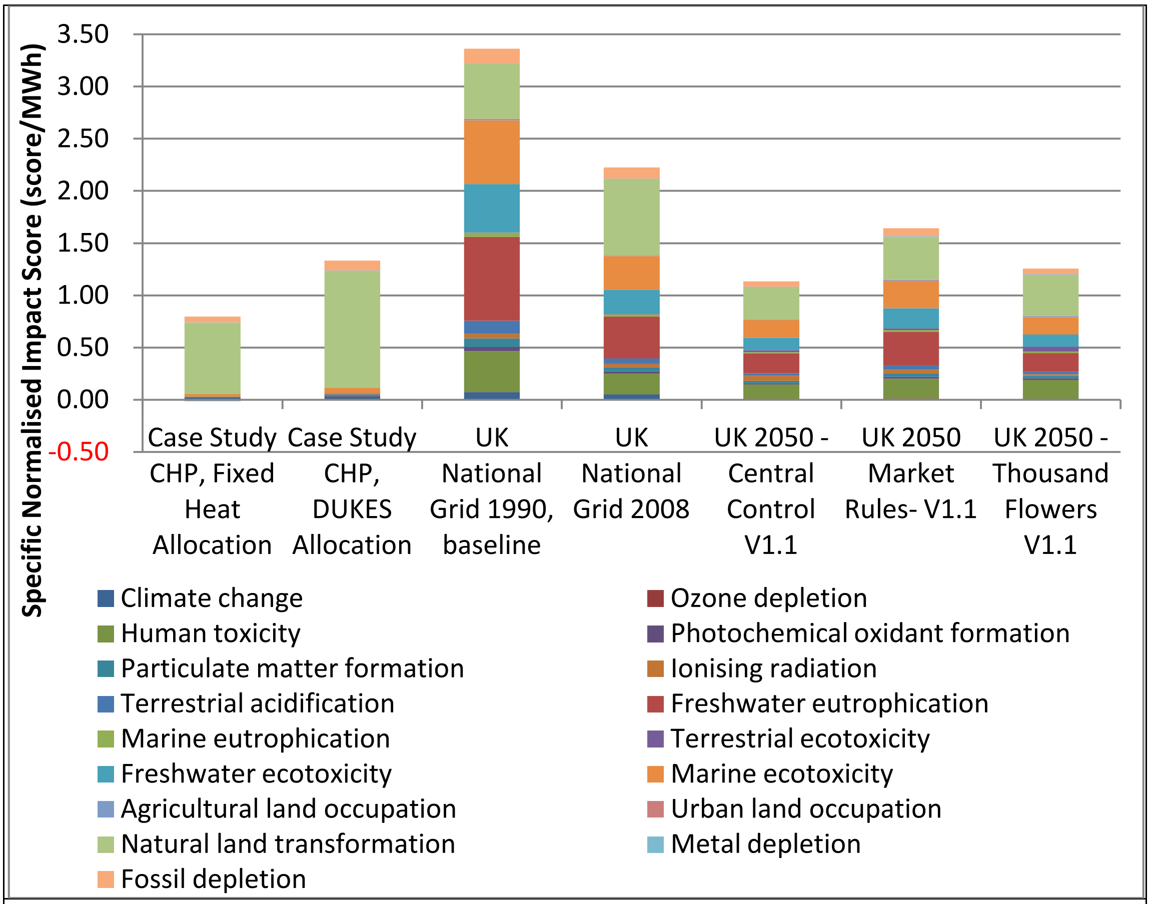

Figure 73 Comparison of specific normalised scores of the case study CHP with that of the UK National Grid, using Midpoint (H European) Analysis

8.9.1.1 Displaced Environmental Impact Payback Period

With these specific impact results, the displaced impact period of the case study CHP power generation can be estimated using:

$$\frac{Life\ Cycle\ Impact\ Case\ Study\ CHP: Power\ Allocation\ Only}{Annual\ Power\ Output \times (Specific\ Impact\ of\ Grid - Specific\ Impact\ of\ Case\ Study\ CHP)}$$

Table 49 presents the power only displaced payback results for each of the allocation methods against the model for natural gas fuelled power generation (Heck 2003) and each of the five National Grid mixes modelled (Hammond, Howard and Jones 2013). Perhaps unsurprisingly, the annual impact savings made against the gas fuelled power only system are not enough to offset the case study CHP within the plants design lifetime, however the fact that there is an annual saving is notable. When the 'fixed heat' allocation is applied, the savings generated per unit power displaced will offset the CHP system well within its 30 year lifetime when compared to the 1990 baseline and 2008 Grids. Most importantly, when this allocation method is used the CHP plant will also payback within 30 years when compared to the Market Rules 2050 Grid mix, providing further confidence that this type of CHP technology could contribute to a future low impact power supply for the UK. When the DUKES allocation method is adopted, the CHP is only offset within the plants 30 year life when it is assumed that it is displacing power from the 1990 baseline National Grid mix, and will never payback in comparison to the Central Control and Thousand Flowers 2050 Grid mix models as the power displacement will come at an impact cost rather than a saving. For comparison, the displaced impact paybacks of the model for natural gas fuelled power only generation against the five representations of the National Grid mix, which exceed any period calculated for the case study CHP, are also tabulated.

	Displaced payback period for gas fired power generation using:		
	Case Study CHP, Fixed Heat Allocation (years)	**Case Study CHP, DUKES Allocation (years)**	***Natural Gas Fuelled Power Generation (years)***
Natural Gas Fuelled Power Generation	40	682	-
UK National Grid 1990, baseline	9	20	*21*
UK National Grid 2008	17	45	*47*
UK 2050 – Central Control V1.1	71	n/a	*n/a*
UK 2050 – Market Rules V1.1	28	129	*134*
UK 2050 – Thousand Flowers V1.1	52	n/a	*n/a*

Table 49 Set of displaced impact payback period results for the power generation only of the case study CHP (to the nearest year)

8.9.2 SPECIFIC CARBON

A total lifetime GWP of the power generation only can be calculated at either 5.013 or 10.03 Mt.CO_2 (equivalent) (to 4 significant figures) using the 'fixed heat' or DUKES allocation methods respectively. Both these GWP allocations are lower than the characterized result for climate change given for the gas fired power only generation presented in Table 45, which alone supports the case that CHP can contribute to a low carbon UK National Grid.

These figures were divided by the total lifetime power output to give the specific carbon emissions shown under the category of climate change in Table 48. Reported carbon intensity per average unit of UK gas fired electricity, which include all technology types, are 403 kg.CO_2eq/MWh(e), 394 kg.CO_2eq/MWh(e) and 392 kg.CO_2eq/MWh(e) for 2009, 2010 and 2011 respectively (Her Majesty's Government 2012, DUKES. Table. 5A). The estimated figure for the case study CHP falls below these values irrespective of which allocation method is adopted, lending further confidence that implementation of more industrial CHP systems can help reduce the carbon intensity of the current UK power supply. Also, these figures are estimated using site emissions only, rather than a full life cycle carbon intensity so comparable figures for average UK gas fired power would actually be slightly higher.

Figure 74 compares the two estimated values for GWP per MWh generated with the same five representations of the National Grid. The GWP for both value estimates for CHP electricity fall below estimates for both the current and 1990 baseline National Grids, but exceed that of the specific GWP estimates for all three representations of the 2050 UK Grid mix.

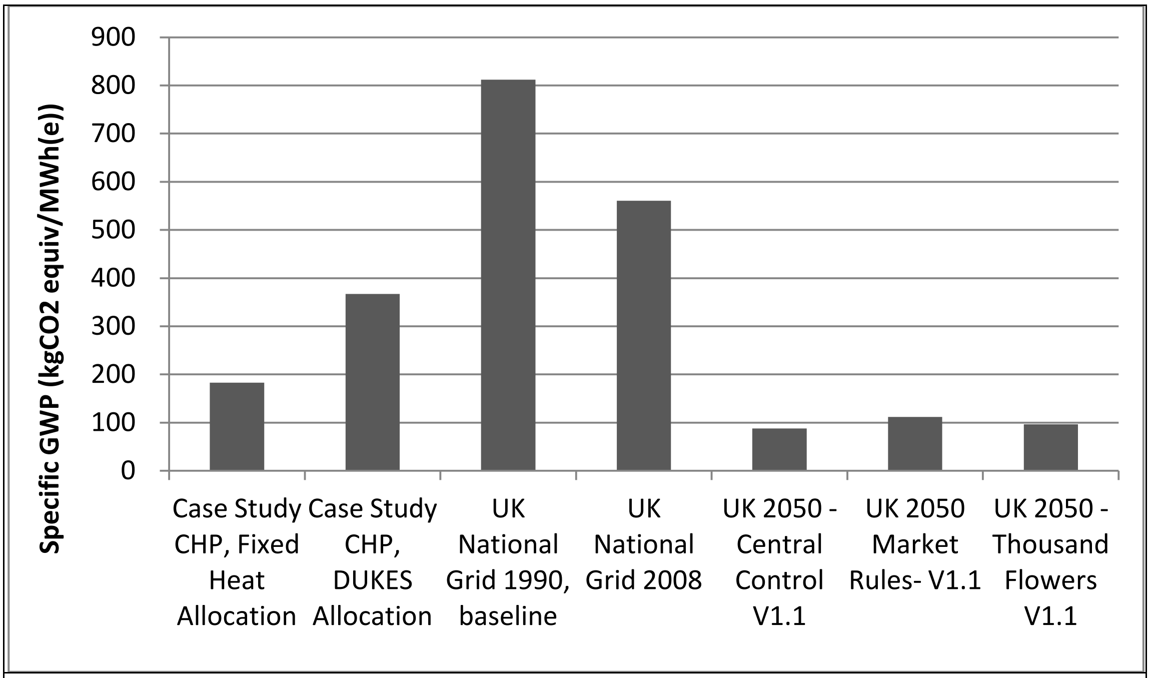

Figure 74 Comparison of specific GWP of the case study CHP with that of the UK National Grid

Carbon equivalent savings or costs per MWh of generation are estimated against the five National Grid mix models and are shown in Table 50. Importantly, when the 'fixed heat' allocation is applied, the saving against the 1990 Grid represents 77%, which almost meets the UK carbon reduction target. When the DUKES allocation is applied the saving represents 55%. However, both values for the GWP of CHP electricity exceed all future scenario estimates. The proportional difference is greater than that of the fossil fuel demand because of the CCS technologies present in all the future scenarios which keep carbon intensity down despite fossil fuel combustion. These results support the suggestion that primary fuelled CHP may eventually cease to offer any carbon benefit over an increasingly decarbonised National Grid and will become a carbon burden.

	Case Study CHP, Fixed Heat Allocation ($kg.CO_2eq/MWh(e)$)	**Case Study CHP, DUKES Allocation ($kg.CO_2eq/MWh(e)$)**
UK National Grid 1990, baseline	629	445
UK National Grid 2008	377	193
UK 2050 – Central Control V1.1	-95	-280
UK 2050 – Market Rules V1.1	-71	-255
UK 2050 – Thousand Flowers V1.1	-86	-271

Table 50 Set of GWP savings and costs per MWh(e) against National Grid mix models (to the nearest kg)

8.9.2.1 Displaced Carbon Payback Period

With these specific emission results, the displaced carbon payback period of the case study CHP power generation can be estimated. Table 51 presents the power only displaced payback results for each of the allocation methods against the model for natural gas fuelled power generation and the two National Grid mixes modelled (Hammond, Howard and Jones 2013) against which the CHP power generation makes a GWP saving, i.e. that of the 1990 baseline and current Grid mix models. The CHP will never payback in comparison to the Transition Pathways 2050 Grid mix models because the power is generated at a carbon cost. When the 'fixed heat' allocation is applied, the savings generated per unit power displaced will still offset the CHP system within its 30 year lifetime when compared to gas fired power generation and to the 1990 baseline and 2008 National Grid mixes. When the DUKES allocation method is adopted, the CHP is only offset within the plants 30 year life when it is assumed that it is displacing power from the 1990 baseline National Grid mix. For comparison, the displaced impact paybacks for natural gas fuelled power generation against the 5 representations of the National Grid mix, which exceed any period calculated for the case study CHP, are also tabulated.

	Displaced payback period for gas fired power generation using:		
	Case Study CHP, Fixed Heat Allocation (years)	**Case Study CHP, DUKES Allocation (years)**	***Natural Gas Fuelled Power Generation (years)***
Natural Gas Fuelled Power Generation	25	301	-
UK National Grid 1990, baseline	9	25	*27*
UK National Grid 2008	15	57	*63*

Table 51 Set of displaced carbon payback period results for the power generation only of the case study CHP (to the nearest year)

8.9.3 SPECIFIC ENERGY

The specific energy demand per energy resource category for the case study CHP, using the two most extreme allocation methods, is given in Table 52. As would be expected the 'fixed heat' method gives a much lower impact allocation to the electricity generated, around 59% less energy demand overall. Again, some negative results are generated when the fixed heat allocation method is applied because of categories where the impact of the reference heat only model is actually greater than that of the case study CHP, most significantly in the resource category of nuclear energy. This is because the heat only system has an operational electricity demand which is met by the National Grid mix which includes a range of technologies. The operational power demand of the case study CHP is met by the CHP itself so the only demand on the National Grid is from up steam processes, which is significantly less than the operational demand.

Impact category	**Unit**	**Case Study CHP, Fixed Heat Allocation**	**Case Study CHP, DUKES Allocation**
Non renewable, fossil	MJ/MWh(e)	4018	6 688
Non-renewable, nuclear	MJ/MWh(e)	-20	10
Non-renewable, biomass	MJ/MWh(e)	0	0
Renewable, biomass	MJ/MWh(e)	0	1

Table 52 Specific energy demand by resource category for the power generated by the case study CHP (to the nearest MJ)

These two options for the impact values for industrial CHP power generation can now be used to investigate the impact savings available in comparison to power production by the National Grid. Figure 75 compares the two estimated values for energy demand per MWh generated with five representations of the National Grid. All the National Grid representations have a higher total energy demand than either of the representations for power from the case study CHP plant, including the three Transition Pathway models for the 2050 Grid mix. However, a high proportion of the energy demand of the future Grid scenarios is made up from energy from nuclear and renewable biomass. If the energy demand from non-renewable fossil fuels is isolated from the total values, the results from the case study CHP model start to look less favourable. The fossil fuel demand of the case study CHP electricity supply exceeds that of all the future scenarios if the DUKES allocation method is applied. If the 'fixed steam' allocation method is applied then the fossil fuel demand still exceeds the Central Coordination and Thousand Flowers scenarios, by about 12% and 4% respectively. However, there is a benefit compared with the Market Rules scenario. This is because of the high proportion of gas and coal fired generation using carbon capture and storage, CCS, technology in this scenario.

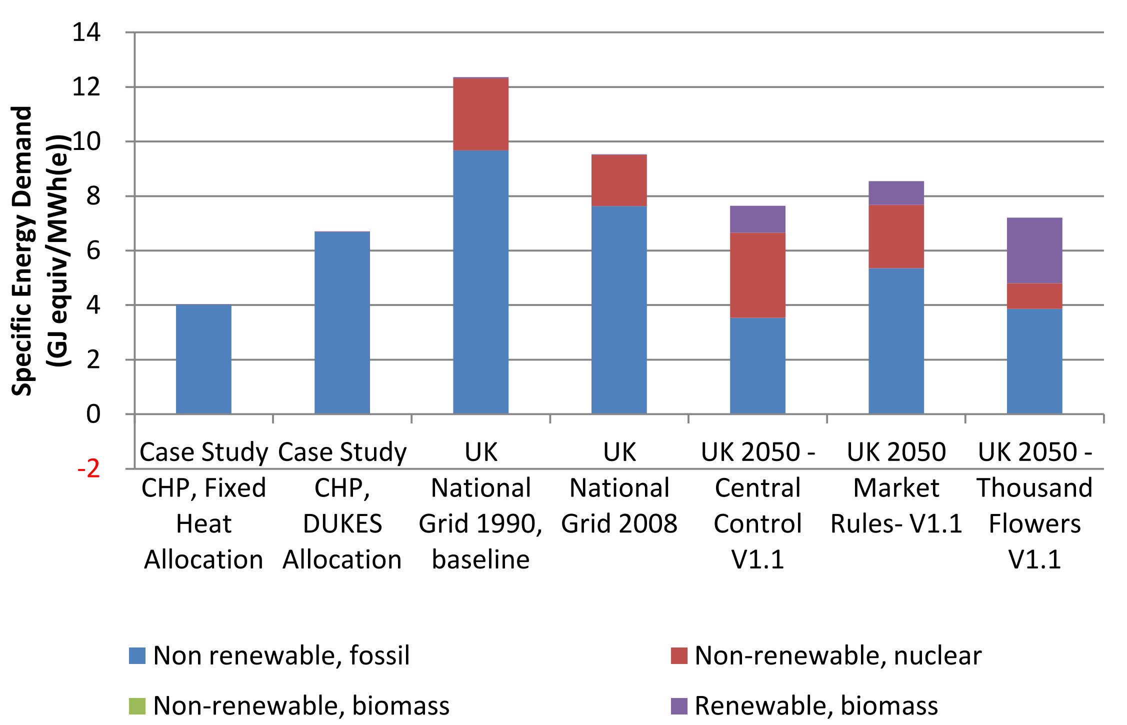

Figure 75 Comparison of specific energy demand of the case study CHP with that of the UK National Grid

8.9.3.1 Displaced Energy Payback Period

Table 53 presents the power only displaced payback results for each of the allocation methods against the UK natural gas fuelled power only model and each of the five National Grid mixes (Hammond, Howard and Jones 2013). Most notably, an impact saving is available in every instance so unlike the results already generated in the overall environmental impact and carbon analysis, a payback period can be calculated in all comparisons. However, as always, it is those instances that payback within the systems lifetime that are of most interest. When the 'fixed heat' allocation is applied, the savings generated per unit power displaced will offset the CHP system well within its 30 year lifetime when compared to the 1990 baseline and 2008 Grids, and again in comparison to the Market Rules 2050 Grid mix model. When the DUKES allocation method is adopted, the annual savings are never sufficient to offset the lifetime energy demand within the plants lifetime.

	Displaced payback period calculated for gas fired power generation using:		
Displaced Power Mix	**Case study CHP, Fixed Heat Allocation (years)**	**Case study CHP, DUKES Allocation (years)**	**Natural Gas Fuelled Power Generation (years)**
Natural Gas Fuelled Power Generation	41	820	-
UK National Grid 1990, baseline	14	36	38
UK National Grid 2008	22	71	81
UK 2050 – Central Control V1.1	33	214	301
UK 2050 – Market Rules V1.1	26	109	130
UK 2050 – Thousand Flowers V1.1	37	395	790

Table 53 Set of displaced energy payback period results for the power generation only of the case study CHP (to the nearest year)

8.10 DIRECT FUEL DEMAND ASSESSMENT: POWER ONLY

Gas consumption for the equivalent annual separate heat and power generation, that is 2,913 GWh(th) of heat and 911 GWh(e) of power, requires 2,214 GWh and 1,751 GWh of natural gas respectively. This gives a total fuel requirement for separate generation of 4,664 GWh, which is 722 GWh greater than the case study CHP fuel demand of 3,942 GWh. This is a saving of 15% so the case study CHP would qualify as 'Good Quality' as set down by the EU Cogeneration Directive (European Parliment 2004) with respect to direct fuel saving.

The assertion that the direct fuel might be better used in power only generation (Watts, et al. 2010) can now be investigated. The electrical fuel efficiency of the case study CHP is given by dividing the power generation only by the overall fuel consumption; this gives a value of 24%. This matches that reported average electrical efficiency of the UK CHP stock and is actually slightly worse than the figure of 27% reported for the average UK combined cycle CHP (Her Majesty's Government 2012, DUKES. Table 7D). This shows that the case study fuel consumption is representative of UK CHP.

Figure 72 has already shown that from an overall environmental impact perspective, power generated by the case study CHP is preferable to that generated by a gas fuelled power only system, irrespective of which method is used to allocate the impact of the power generated. This implies that the fuel demand of the power only system is higher than that of the power generated by the case study CHP, as the fuel is typically the most impactful entry in the systems life cycle inventory. To investigate this further, the direct fuel requirement for the power generated by the case study CHP was calculated, using the three suggested allocation methods, and the results are shown in Table 54. It can be seen that the direct fuel demand for power generation by the case study CHP is less than that of a power only system model.

Note, this is not life cycle energy analysis, that would include the up and down stream, or indirect, fuel demands whereas here only the direct consumption is considered. This means that the case study results can be more easily compared with publically available fuel efficiency data for gas fired power generation. UK overall gas fired power efficiency was reported to be 47% (in 2008, 2009 and 2010)(Her Majesty's Government 2011, from data in Tables 5.1 & 5.4) which would imply a gas demand of 1,938 GWh to generate 911 GWh(e). This implies that the case study CHP power generation is more fuel efficient than the current UK gas plant stock. However, this figure is likely to include some older plants that have poor efficiencies compared to the newer technologies that they might be replaced with before 2050. CCGT systems are typically cited as the most efficient method for generating power from gas and existing systems reach a maximum of 60%, although some companies are reporting hardware that could better this (Robb 2010). Assuming 60%, however, 1,518 GWh of gas would be required to generate the equivalent yearly capacity of the case study CHP (911 GWh). The CCGT efficiency used for reference in the Max Fordham study is 58% which leads to a comparable gas requirement of 1,571 GWh (Watts, et al. 2010). These figures both fall below the estimated fuel demand of the case study CHP using the DUKES allocation method but are greater than the estimates using the other two allocation methods. These results suggest that the fuel efficiency of CHP power in comparison to alternative gas fired power generators is likely to be highly reliant on the nature of the heat demand. This supports the initial hypothesis that the priority case for CHP implementation should be where there is an established heat load.

	Unit	Case Study CHP, Fixed Heat Allocation	Case Study CHP, DUKES Allocation	Case Study CHP, Percentage Allocation
Fuel required by Case Study CHP to generate 911 GWh(e)	GWh	1 029	1 680	1 480

Table 54 Annual direct fuel requirement for power generation of Case Study CHP (to the nearest GWh)

8.11 SUMMARY

A life cycle inventory was developed for the E.On operated CHP plant in Winnington, UK. The plant is a large industrial heat lead system fuelled by natural gas, which meets the case study criteria identified via the literature analysis. Subsequent impact assessment has shown that conversion from a heat only system to a CHP system will lead to increases in both environmental impact and energy demand. However, the study has shown that the additional impact cost leads to considerable impact savings when the system is compared to the sum impact of separate heat and power generation.

Allocation options have been explored to identify the impact of the power generated for comparisons with National Grid mix models. The 'fixed heat' allocation method was developed which assumes CHP plant is installed in place of a heat only system and hence at least the equivalent impact of the heat only system can be allocated to the heat generated by the CHP and only impacts which are above that amount should be allocated to the power generation. This method as well as that developed by DUKES (Her Majesty's Government 2011, DUKES. para. 6.39), are used throughout the comparisons of specific impact per unit of power generated. In this way, it has been shown that impact savings can be made by generating power via a CHP system in comparison to a power only system, irrespective of which allocation method is adopted; although when the DUKES allocation method is applied the saving is very small. A direct fuel assessment has also shown that the fuel allocated to power generation in the CHP system would not generate more power if invested in power only system. It has also been shown that considerable impact and energy savings are available when the power allocation only is compared to the current and 1990 baseline National Grids. Importantly the study has demonstrated that industrial CHP has the potential to generate electricity at a 77% carbon equivalent saving per MWh compared to the 1990 baseline National Grid. Exploiting the available industrial heat load to generate electricity via CHP has significant potential to reduce carbon intensity of National electricity supply, as well as overall environmental impact and energy consumption, in the immediate term. However, when the case study CHP power generation is compared to potential future Grids, assessing the benefits becomes more complex. The study has shown that power generated by industrial CHP that replaces an equivalent heat only system has the potential to yield an overall environmental impact saving against the specific impact estimated for the Transition Pathways 2050 National Grid mix scenarios and, hence, CHP can contribute to a lower impact future UK power supply. However, the study has also shown that the GWP of fossil fuelled CHP is likely to exceed that of all the 2050 National Grid mixes per MWh generated, and as hypothesized CHP generated power would at some point become a carbon burden on an increasingly decarbonised future UK National Grid. This contradictory conclusion between overall environmental impact and GWP in isolation begins to highlight some of the wider issues that can be over looked when assessing decarbonisation alone. The CHP system also offers overall energy savings compared to the future UK electricity grid. However, it is likely that the energy demand from fossil fuels alone will exceed that of the 2050 National Grid, although this is dependent on the proportion of CCS technology deployed.

Table 55 summarises the main findings of the case study. The percentage savings available against separate energy generation in all impact indicators considered can be seen. The EGR is less than 1 and the simple payback is greater than its design life, showing that the system will consume more energy than it generates, but this is typical for fossil fuelled systems are the results are good compared to other technologies. The large variation in performance depending on the allocation method adopted can be seen. Importantly, this shows that the impact, energy demand and direct fuel savings that the power generated can offer in comparison to possible future Grid mixes and technologies are highly dependent on the nature of the heat demand. This supports the originally hypothesis that additional CHP implementation should be prioritised at sites where there is an established heat load that would otherwise be met be a heat only system.

SAVING COMPARED TO SEPARATED GAS FUELLED HEAT AND POWER GENERATION		
Total Normalised Environmental Impact Score		16%
Carbon (equivalent) emissions		20%
Energy Demand		16%
Direct Fuel Consumption		15%
ENERGY ANALYSIS MAIN RESULTS		
Life time energy demand (PJ)	Energy Gain Ratio	Energy Payback period (yrs)
430	0.8	35
CARBON ANALYSIS MAIN RESULT		
Life time carbon emissions ($Mt.CO_2eq$)		24
	Specific carbon emissions ($kg.CO_2eq/MWh(e)$)	Displaced Carbon Payback Period (years), against National Grid mix - baseline(1990)/current (2008)
Case Study CHP, Fixed Heat Allocation	183	9/15
Case Study CHP, DUKES Allocation	367	25/57
CARBON SAVINGS COMPARED TO NATIONAL GRID		
	Case Study CHP, Fixed Heat Allocation ($kg.CO_2eq/MWh(e)$)	**Case Study CHP, DUKES Allocation ($kg.CO_2eq/MWh(e)$)**
UK National Grid 1990, baseline	629	445
UK National Grid 2008	377	193
UK 2050 – Central Control V1.1	-95	-280
UK 2050 – Market Rules V1.1	-71	-255
UK 2050 – Thousand Flowers V1.1	-86	-271

Table 55 Case study: Winnington CHP - summary table of main findings

By far the greatest impact is still due to the fuel demand. In order to investigate the potential of further impact reductions, the case study plant was reassessed assuming that the full fuel demand is met by bio-gas.

CHAPTER 9. WINNINGTON IMPROVEMENT ANALYSIS: ALTERNATIVE FUEL

9.1 IN THIS CHAPTER

The case study plant was re-assessed but under the assumption that purified bio-gas, derived from waste streams, is used to fuel the plant and presents the impact improvements that are identified

9.2 ADDITIONAL INVENTORY ANALYSIS

The LCA case study identified that by far the largest contributor to all the impact indicators investigated was from the natural gas consumption. Hence, it was concluded that the most effective way to reduce the impact of the CHP system would be to use a lower impact gas. As discussed in Section 7.7, one option for low impact gas is bio-gas derived from household waste.

To investigate the potential further savings that could be made by switching from a fossil to bio-fuelled system, the LCI for the case study CHP was altered such that the fuel demand was met by bio-gas supplied via the UK gas network rather than natural gas. The bio-gas supply model assumes a production mix of 48% bio-gas from organic waste and 52% bio-gas from sewage sludge. The bio-gas is supplied by a network identical to the UK supply network used for the natural gas supply in the original case study model; specifically, the gas supply network assumes the same leakage rate as that assumed for the natural gas supply model, i.e. 0.0245m^3 of gas input is required per 1MJ supplied to the consumer. The gas is purified to meet the network standard, which requires 0.065 Wh of power supplied by the UK 2008 Grid mix per 1MJ of purified gas. The model is based on an EcoInvent database entry (Spielmann 2007) with appropriate edits. Further to this, all the carbon dioxide, carbon monoxide and methane emissions entered in the case study CHP inventory as per the environmental report provided by the site were changed to biogenic rather than fossil emissions, although the volume of emissions were unaltered.

The models developed for separate gas fuelled heat and power generation were also edited in order to represent bio-fuelled energy generation alternatives. The fuel consumption was switched to an equivalent amount of the UK bio-gas described and all fossil emissions were switched to biogenic.

9.3 LIFE CYCLE ASSESSMENT RESULTS INTERPRETATION

Table 56 gives the characterized results for the full life cycle of the case study CHP when it is assumed that the fuel demand is met by bio-gas and the impact difference for each category when compared to the results of the natural gas model, shown as impact savings or costs. All the savings made over the natural gas fuelled system will obviously be all at Operation as this is the only stage where any changes have been made. As might be expected, savings of over 100% of the total impact of the bio-fuelled system are available in the categories of natural land transformation and fossil fuel depletion as the contribution to these categories from the plant direct fuel combustion is almost entirely removed by switching to bio-gas; the remaining impact is from fossil fuelled energy demand for up-stream processes. Large savings are also available in the categories of climate change and ozone depletion because of the biogenic nature of the site emissions, although these savings do not exceed the total impact of the bio-gas CHP model. However, most significantly it can be seen that in every other category the fuel change comes at an impact cost. This is largely due to the additional chemicals and infrastructure required to produce and purify bio-gas.

Impact category	Unit	Case Study CHP Model, fuelled by Bio-gas	*Saving/cost over Natural Gas fuelled CHP system*
Climate change	kg.CO_2eq	17 992 100 000	*5 549 850 000*
Ozone depletion	kg.CFC-11-eq	566	*380*
Human toxicity	kg.1,4-DB-eq	2 703 430 000	*-2 521 160 000*
Photochemical oxidant formation	kg.NMVOC	33 060 500	*-17 225 700*
Particulate matter formation	kg.PM10-eq	13 174 900	*-8 737 510*
Ionising radiation	kg.U235-eq	2 910 370 000	*-2 844 860 000*
Terrestrial acidification	kg.SO_2-eq	46 784 800	*-35 675 700*
Freshwater eutrophication	kg.P-eq	2 252 290	*-2 110 710*
Marine eutrophication	kg.N-eq	9 930 180	*-4 378 610*
Terrestrial ecotoxicity	kg.1,4-DB-eq	376 299	*-315 818*
Freshwater ecotoxicity	kg.1,4-DB-eq	48 789 200	*-45 176 100*
Marine ecotoxicity	kg.1,4-DB-eq	52 094 100	*-25 828 700*
Agricultural land occupation	m^2	176 779 000	*-170 048 000*
Urban land occupation	m^2	74 174 600	*-58 121 200*
Natural land transformation	m^2	2 215 110	*9 410 320*
Water depletion	m^3	185 683 000	*-34 437 500*
Metal depletion	kg.Fe-eq	803 522 000	*-688 947 000*
Fossil depletion	kg.oil-eq	2 374 010 000	*7 839 140 000*

Table 56 Characterised results by impact category of bio-gas fuelled CHP and the savings available in comparison to an equivalent natural gas fuelled CHP, using Midpoint (H European) Analysis (to 6 significant figures)

Figure 76 compares the normalized scores for each impact category of the natural gas and bio-gas fuelled CHP models. The considerable impact savings in the, previously identified most 'significant', category of natural land transformation is evident. However, the highest impact score for the bio-gas fuelled system, in a normalized context, is still in the category of natural land transformation. This is because the UK 2008 specific National Grid mix that supplies the gas purification process has a high proportion of off-shore natural gas fuelled generation. It can be seen that the increased impacts in the categories of human toxity, terrestrial acidification, freshwater eutrophication and freshwater ecotoxity now register in the normalized context whereas in the natural gas model the scores in these categories were negligible.

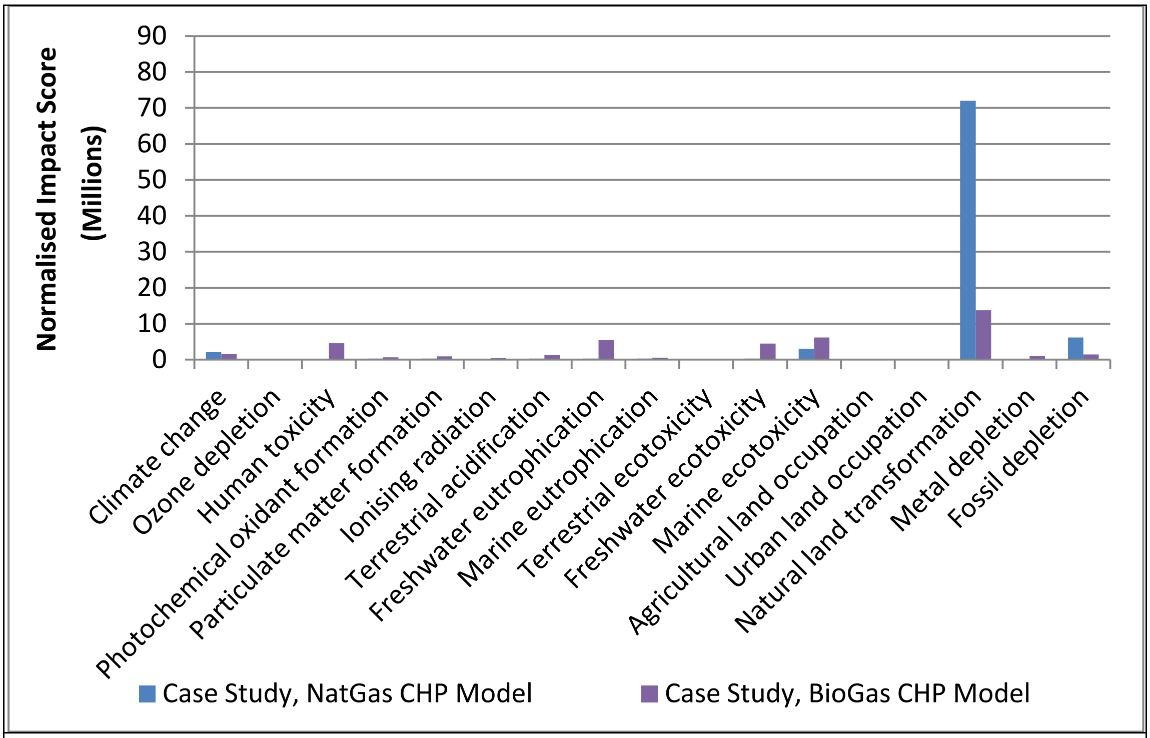

Figure 76 Comparison of normalised scores per impact category for the natural gas and bio-gas fuelled case study CHP models

Figure 77 shows the same data as Figure 76 but summed per system model so that the total normalized impact score, or environmental burden, can be compared. The impact score increases across the suite of impact categories caused by the fuel change can clearly be seen. However the overall impact is, obviously, significantly reduced. The bio-gas fuelled CHP model has a total lifetime impact score of 42.7 million and an annual impact score of 1.4 million. This yields a saving of almost exactly 50% over the natural gas fuelled plant.

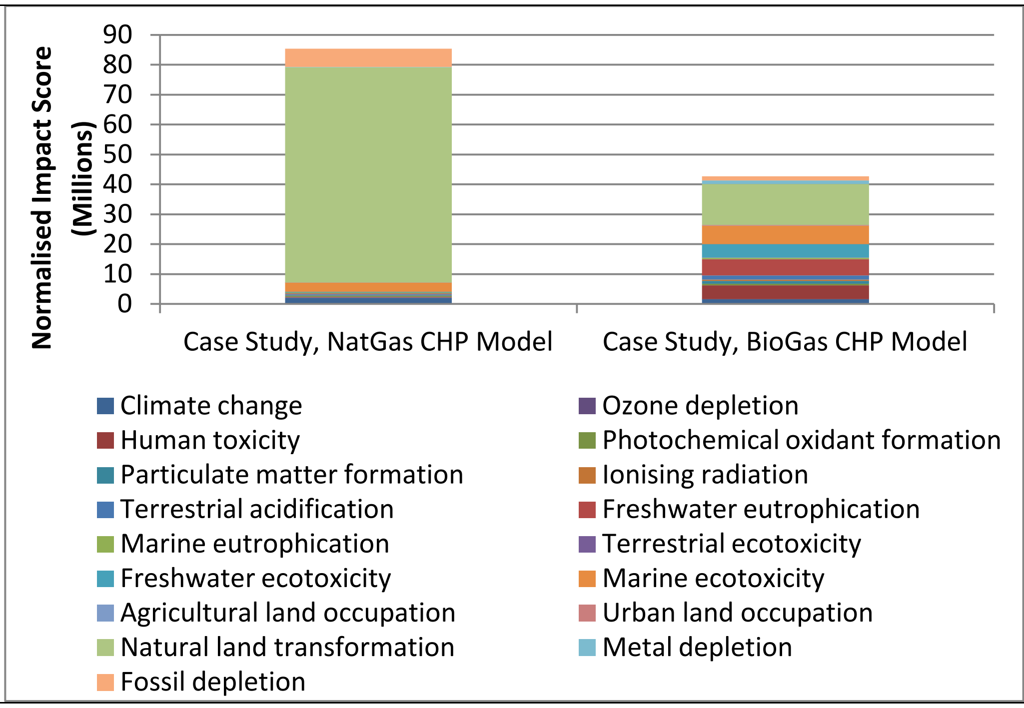

Figure 77 Comparison of the total normalised scores for the natural gas and bio-gas fuelled case study CHP models

Figure 78 shows how the total impact of the bio-gas fuelled CHP is distributed over the plant's four life stages. Although all the savings made over the natural gas fuelled system are at the Operation stage, this stage clearly remains the most impactful stage and natural land transformation remains the dominate impact at this stage, because of the up-stream, in direct natural gas demand of the bio-gas production process, as already discussed.

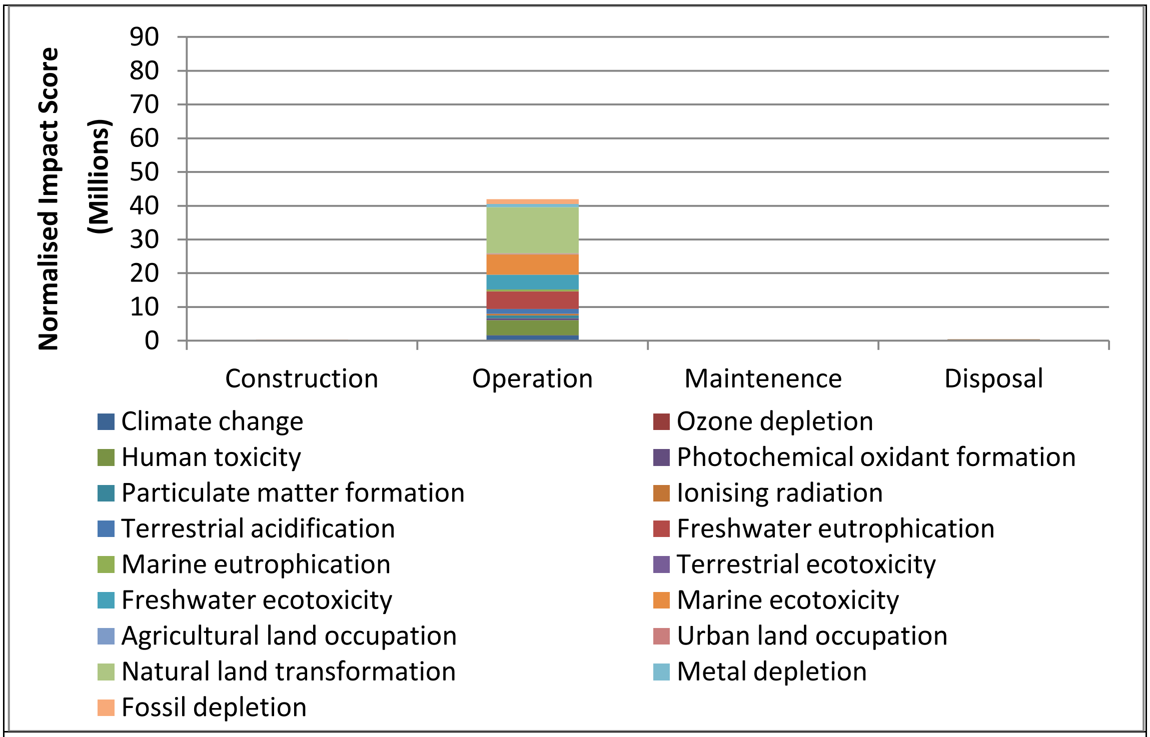

Figure 78 Normalised scores per life stage for the bio-gas fuelled case study CHP

9.3.1 CARBON ANALYSIS

The model assumes that the combustion of bio-gas releases exactly the same amount of carbon dioxide and methane emissions as the combustion of an equal amount of natural gas as they are the same chemical compound, i.e. methane. However, in accordance with the IPCC guidelines, the assumption that all of the carbon dioxide and methane emissions are biogenic significantly reduces their GWP. In fact, in the case of carbon dioxide, the GWP is completely removed. Table 56 shows that, over a 30 year lifetime, GWP could be reduced by around 5.5 Mt.CO_2 (equivalent) by switching identical CHP plants from natural to bio-gas. This represents a saving of 24%.

9.3.2 ENERGY ANALYSIS

Table 57 presents the lifetime energy demand per energy resource category for the case study CHP when fuelled by bio-gas and the savings or cost per category over the natural gas fuelled CHP model. As might be expected, the saving in the category of non-renewable fossil fuel is substantial and represents 77% of the demand estimate for the natural gas CHP, and is over 100% of the bio-gas demand estimate. There is also a substantial saving in the category of non-renewable biomass, this is because the manufacturing process for the pipes used to supply the gas requires a palm oil based soap, and as the natural gas is assumed to be supplied by an off shore well a considerable length of pipe, and hence a considerable amount of palm oil soap, is required. The palm oil is considered non renewable as it is assumed that it is grown on land that was previously virgin forest. The large increases in energy demand in the remaining resource categories are because of the additional electricity required in the upstream production and purification processing of the bio-gas. As above, the contribution from natural renewable energy is included for completeness but will be excluded from subsequent energy analysis. As such, the total lifetime energy demand figure of 129,846 TJ, to the nearest TJ, will be used.

Impact category	Unit	Case Study CHP Model, fuelled by Bio-gas	Saving/cost over Natural Gas fuelled CHP system
Non renewable, fossil	GJ	99 614 296	329 217 575
Non-renewable, nuclear	GJ	29 316 791	-28 658 699
Non-renewable, biomass	GJ	129	142
Renewable, biomass	GJ	915 213	-840 973
Renewable, wind, solar, geothermal	*GJ*	*487 881*	*-477 160*
Renewable, water	*GJ*	*4 100 546*	*-3 998 779*

Table 57 Lifetime energy demand per energy resource category by life stage for each impact category for the bio-gas fuelled CHP and the savings available in comparison to an equivalent natural gas fuelled CHP (to the nearest GJ)

Figure 79 compares the total energy demand of the case study CHP when fuelled by natural gas and when fuelled by bio-gas. The savings are plain and can be seen to be due to the reduction in fossil fuel demand.

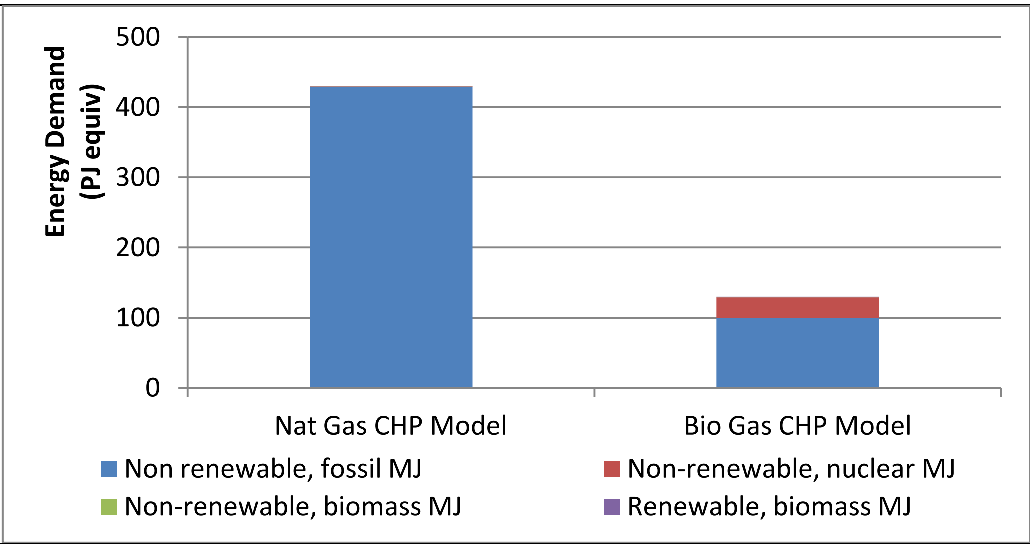

Figure 79 Comparison of lifetime energy of case study CHP when fuelled by natural gas and when fuelled by bio-gas

The energy output of the plant must remain constant, i.e. at 264,902 TJ of heat and 98,392 TJ of power which gives a total energy output greater than the estimated energy demand. Hence the EGR of the bio-gas CHP is 2.8. This is a considerable improvement on the EGR of the natural gas model, of 0.8. A bio-fuelled system can reach an EGR of more than one as the energy required to produce biomass is substantially from renewable natural resources, i.e. solar and other biomass, which are not accounted for as they are not 'consumed' in the normal way. The energy payback period is also significantly reduced to 11 years, to the nearest year, demonstrating that the energy generated by a bio-gas fuelled CHP plant will exceed its estimated lifetime energy demand by the end of its eleventh year of operation.

9.4 SAVINGS COMPARED TO SEPARATE GENERATION

The bio-gas fuelled case study CHP yields a normalized impact saving of 42% over separate natural gas fuelled generation, see section 8.8. This gives a reduced displaced impact payback period of 22 years, which is within the plant assumed lifetime of 30 years. However, although it is in generally thought that it is more feasible to switch a CHP system to operate on bio-fuels, it is also possible to generate heat and power separately using the same bio-fuel. Hence it is appropriate to also compare the bio-gas fuelled CHP model with bio-fuelled separate generating technologies. Table 58 gives the characterised impact results for the equivalent lifetime heat and power generation of the case study CHP generated by separate bio-gas fuelled systems and the savings achieved by the bio-gas fuelled CHP when compared to separate bio-gas generation.

Impact category	Unit	Bio-Gas Fuelled Power Generation (27 331 GWh(e))	Bio-Gas Fuelled Steam Generation (73 584 GWh(th))	Bio-Gas Case Study CHP Lifetime Saving (30yrs)
Climate change	kg.CO_2eq	7 988 170 000	13 474 600 000	3 470 650 000
Ozone depletion	kg.CFC-11-eq	245	415	94
Human toxicity	kg.1,4-DB-eq	1 166 850 000	2 028 390 000	491 804 000
Photochemical oxidant formation	kg.NMVOC	19 209 000	22 066 300	8 214 760
Particulate matter formation	kg.PM10-eq	6 553 820	8 878 630	2 257 550
Ionising radiation	kg.U235-eq	1 277 843 000	2 221 250 000	588 722 000
Terrestrial acidification	kg.SO_2-eq	22 297 600	32 330 800	7 843 580
Freshwater eutrophication	kg.P-eq	969 304	1 711 120	428 137
Marine eutrophication	kg.N-eq	6 099 680	6 420 840	2 590 330
Terrestrial ecotoxicity	kg.1,4-DB-eq	160 647	285 841	70 189
Freshwater ecotoxicity	kg.1,4-DB-eq	21 010 000	36 648 400	8 869 190
Marine ecotoxicity	kg.1,4-DB-eq	22 475 400	38 993 400	9 374 720
Agricultural land occupation	m^2	76 939 700	133 867 000	34 027 400
Urban land occupation	m^2	32 741 900	55 602 000	14 169 300
Natural land transformation	m^2	966 488	1 647 930	399 306
Water depletion	m^3	56 924 800	150 871 000	22 112 400
Metal depletion	kg.Fe-eq	326 650 000	554 713 000	77 841 300
Fossil depletion	kg.oil-eq	1 032 970 000	1 799 890 000	458 859 000

Table 58 Characterised results by impact category of separate bio-gas fuelled generation of the equivalent lifetime energy load of the case study CHP, using Midpoint (H European) Analysis (to 6 significant figures)

Figure 80 shows some of the results generated by the primary case study as it compares the total normalised impact score, or environmental burden, for the life cycle of the case study

CHP when fuelled by natural gas with that of the models for separate natural gas fuelled energy generation but this is then also compared with the total normalized impact score for the bio-gas fuelled case study CHP model and with equivalent heat and power generated by separate bio-gas fuelled generation. The significant impact saving that the bio-gas CHP system can make compared to either CHP or separate natural gas fuelled energy generation is evident; the total impact of the bio-gas CHP falls well below that of the natural gas heat only generation. However, so does the total impact of separate heat and power generation when fuelled by bio-gas. In a similar pattern to that of the natural gas systems, the bio-gas CHP system has a higher overall impact than that of the bio-gas heat only system but the a lower impact than if the total lifetime heat and power were generated by separate bio-gas fuelled systems, as perhaps would be expected.

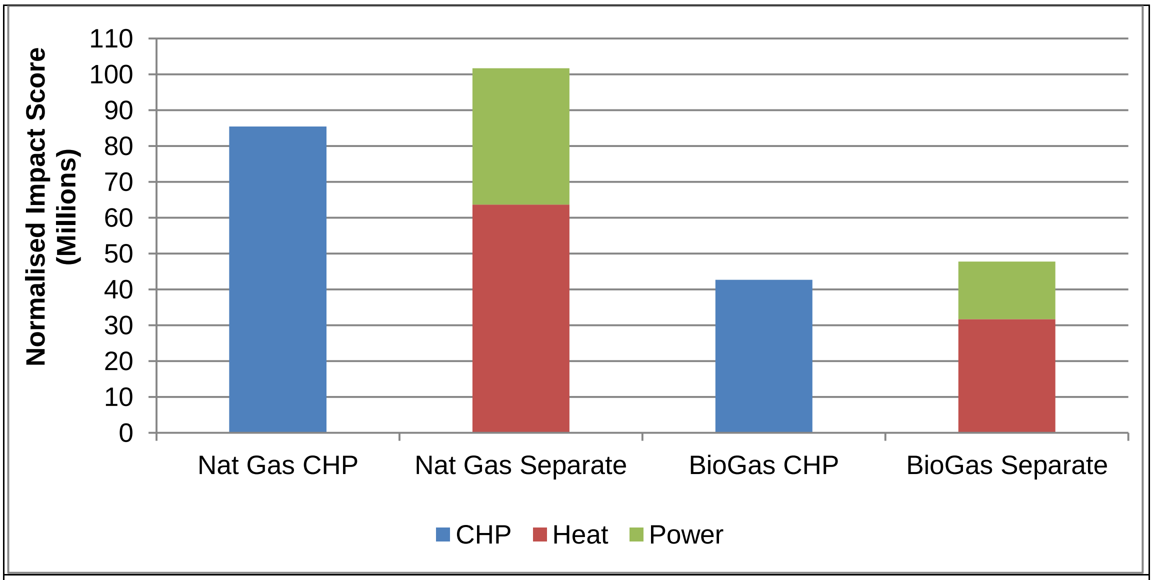

Figure 80 Comparison of total normalised impact score for the case study CHP with the equivalent amount of life time heat and power generated using separate for different fuel types, using Midpoint (H European) Analysis

Table 59 provides the information required to calculate the total impact savings available in comparison with separate bio-gas fuelled energy generation. It can be seen that when all system are assumed to be fuelled by bio-gas, then impact savings that can be made by adopting CHP system over equivalent separate heat and power generation could be 11%. This is still a significant saving but is less than the 16% saving available when all systems are assumed to be fuelled by natural gas. When the bio-gas fuelled CHP is compared with bio-gas separate generation, the displaced impact payback period is increased to 250 years.

	Annual Total Normalised Impact Score	Lifetime Total Normalised Impact Score
Separate bio-gas fired electricity production (Heck 2003)	537 600	16 130 000
Separate bio-gas fired steam production (Zah 2007)	1 056 000	31 680 000
Case study CHP	1 423 000	42 690 000
Impact savings	170 600	5 118 000

Table 59 Information required to calculate bio-fuelled CHP impact improvements over separate bio-fuelled energy generation using Midpoint (H European) Analysis (4.s.f.s)

9.4.1 CARBON

The bio-gas CHP achieves a saving of 11.59 $Mt.CO_2$ (equivalent) (to 4 significant figures) over its 30 year life when compared to separate natural gas fuelled energy generation. Table 58 shows that when the bio-gas CHP is compared to separate energy generators that are also bio-gas fuelled, the available saving 3.471 $Mt.CO_2$ (equivalent) (to 4 significant figures), which is less than the saving estimated for displacing separate generation systems with a CHP when all systems are natural gas fired.

Notably, the saving that could be achieved by simply switching the fuel consumed by the separate energy generators is 8.118 $Mt.CO_2$ (equivalent) (to 4 significant figures) which is greater than the saving estimated for displacing separate generation systems with a CHP when all systems are natural gas fired, suggesting that the case for fuel switching rather than whole technology change warrants further investigation. This is outside the scope of this research but is noted in section 11.1.2.

9.4.2 ENERGY

Compared to the energy demand of equivalent heat and power generated by separate natural gas fuelled systems, see section 8.8.3 , the bio-fuelled case study CHP can offer an energy demand saving of 380,234 TJ over its 30 year lifetime, this represents a saving of 89% which is a substantial improvement of the savings available from natural gas fuelled CHP. This comparison yields a displaced payback period of only 10 years.

However when the bio-gas CHP is compared to separate bio-gas fuelled energy generation, as presented in Table 60, the lifetime energy savings are reduced to 16%, and the displaced payback period is extended to 153 years. This is a similar saving and a slight improvement on the displaced payback period, of 160 years, that was calculated when comparing natural gas fuelled CHP and separate generation.

	Annual Energy Demand, TJ	**Lifetime Energy Demand, TJ**
Separate bio-gas fired electricity production (Heck 2003)	1 888	56 641
Separate bio-gas fired steam production (Zah 2007)	3 289	98 680
Case study CHP	4 328	129 846
Impact savings	849	25 475

Table 60 Information required to calculate bio-fuelled CHP impact improvements over separate bio-fuelled energy generation (to nearest TJ)

9.5 LIFE CYCLE ASSESSMENT RESULTS INTERPRETATION: POWER (ONLY) IN CONTEXT

There are two options for the 'fixed heat' allocation method: where it is assumed that the heat allocation should be equal to a) a natural gas fired heat only system or b) a bio-gas fuelled heat only system. When a) is adopted, the allocation for the power generated by the bio-gas fuelled CHP will yield an overall negative result, or an impact benefit, as the impact of the whole CHP system is less than that of the natural gas fired steam only model. These results will help to identify and quantify the benefits of bio-gas over natural gas fuelled power outputs and where they are made. When b) is adopted, then a more realistic power allocation for comparison with other power generating systems is generated. Table 61 gives the specific characterized results per unit of power generated by the bio-gas fuelled case study CHP using both natural gas and bio-gas 'fixed heat' allocation options as well as the DUKES allocation method. Comparing these allocation approaches, it can clearly be seen that the bio-gas fuelled system would have increased impacts in a number of categories over a natural gas system, particularly in the categories of human toxicity and metal depletion. As already mentioned this is due to the additional up stream processes required to purify the bio-gas.

Impact category	Unit	Bio Gas CHP, Fixed Heat (Natural Gas) Allocation	Bio Gas CHP, Fixed Heat (Bio Gas) Allocation	Bio Gas CHP, DUKES Allocation
Climate change	kg.CO_2eq/MWh(e)	-20	165	281
Ozone depletion	kg.CFC-11-eq/MWh(e)	0	0	0
Human toxicity	kg.1,4-DB-eq/MWh(e)	93	25	42
Photochemical oxidant formation	kg.NMVOC/MWh(e)	1	0	1
Particulate matter formation	kg.PM10-eq/MWh(e)	0	0	0
Ionising radiation	kg.U235-eq/MWh(e)	102	25	45
Terrestrial acidification	kg.SO_2-eq/MWh(e)	1	1	1
Freshwater eutrophication	kg.P-eq/MWh(e)	0	0	0
Marine eutrophication	kg.N-eq/MWh(e)	0	0	0
Terrestrial ecotoxicity	kg.1,4-DB-eq/MWh(e)	0	0	0
Freshwater ecotoxicity	kg.1,4-DB-eq/MWh(e)	2	0	1
Marine ecotoxicity	kg.1,4-DB-eq/MWh(e)	1	0	1
Agricultural land occupation	m^2/MWh(e)	6	2	3
Urban land occupation	m^2/MWh(e)	2	1	1
Natural land transformation	m^2/MWh(e)	0	0	0
Water depletion	m^3/MWh(e)	2	1	3
Metal depletion	kg.Fe-eq/MWh(e)	28	9	13
Fossil depletion	kg.oil-eq/MWh(e)	-191	21	37

Table 61 Specific characterised results by impact category for the power generated by the bio-gas fuelled CHP, using Midpoint (H European) Analysis (to the nearest whole unit)

Figure 81 compares the specific total normalized impact scores for the power generated by the bio-gas CHP, using the three allocation options, with that of the five representations of the UK National Grid. It can be seen that although the characterized result in the category of natural land transformation was negligible for all allocation methods, when normalized the bio-gas CHP has a significant impact saving when the 'fixed heat' allocation is used with reference to a natural gas fuelled heat only system, indicated by the negative normalized score. For obvious reasons, there is also a small normalized impact benefit in the category of fossil fuel depletion. However, the negative score in the category of natural land transformation alone is greater than the sum of the positive scores so, as expected the bio-gas CHP has a net total impact saving when this allocation method is adopted due, almost, entirely to the huge reduction in natural land use.

Markedly, the specific impact of the power generated by the bio-gas CHP, irrespective of allocation method, falls below all representations of the National Grid, even if only the positive impact scores are considered. Perhaps most importantly, all impact allocations for the power generated by the bio-gas CHP also fall below the 'fixed heat' specific power allocation of the natural gas CHP. If the only the positive impact scores are considered in the case of the 'fixed heat' allocation for the bio-gas CHP power with reference to a natural gas heat only system, then the impact increases in these categories only equals, rather than exceeds, the net impact of the 'fixed heat' allocation of the natural gas CHP power. All these results demonstrate that despite the impact increases in the majority of impact categories over natural gas fuelled power, the power generated by the bio-gas CHP is the lowest overall impact choice, in the current normalized context.

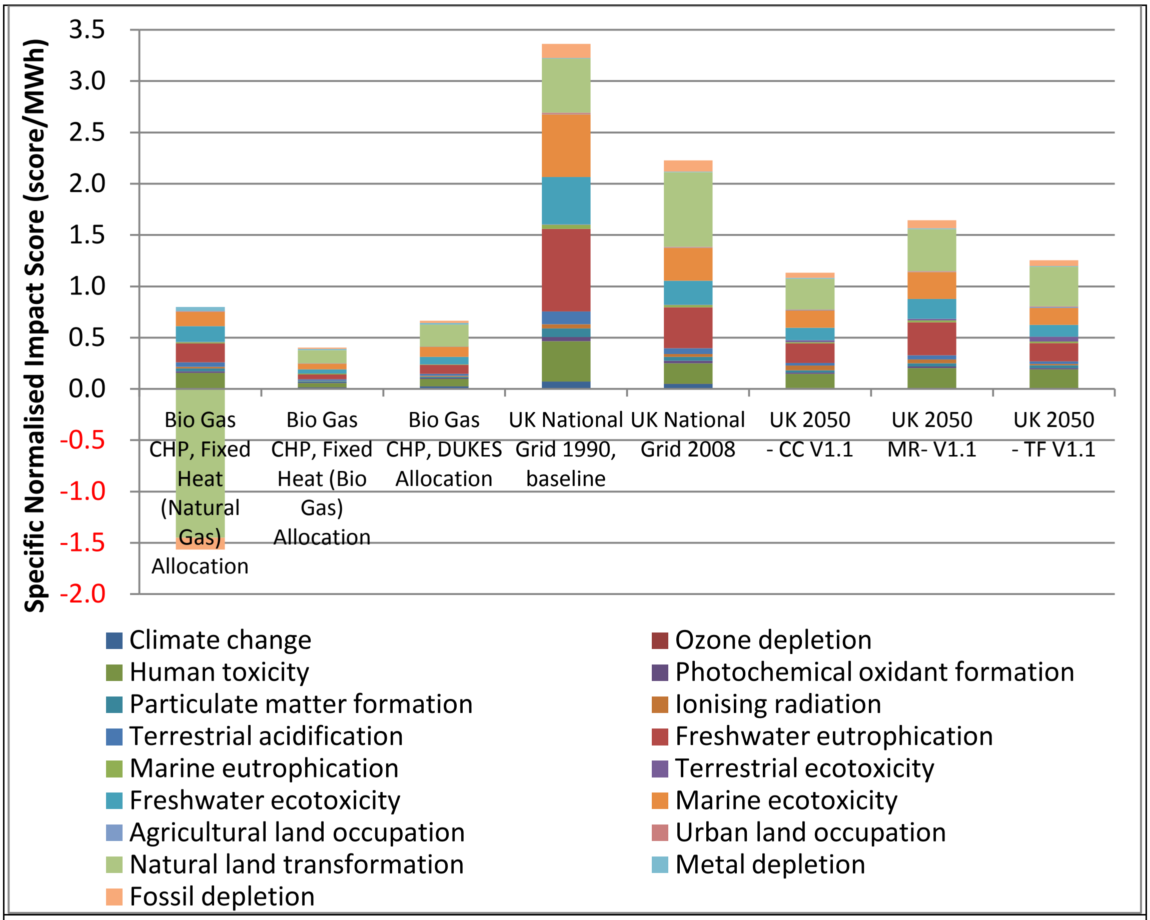

Figure 81 Comparison of specific normalised scores of the bio-gas fuelled CHP with that of the UK National Grid, using Midpoint (H European) Analysis

As the lifetime impact allocation for the power generated by the bio-gas CHP is negative when the 'fixed heat' allocation is used with reference to a natural gas fuelled heat only system, the system is never in any impact 'debt' so no payback period is required when this allocation method is adopted. Table 62 presents the displaced impact payback periods for the remaining power allocation options against the natural gas fuelled CHP model and each of the five representations for the National Grid. Using the 'fixed heat' allocation method, with reference to a bio-gas heat only system, the bio-gas CHP power generation will pay back within the plants assumed 30 year lifetime irrespective of what power generation method it is assumed to displace.   Even when the DUKES allocation is applied, the bio-gas CHP will payback well within its lifetime when it is assumed that it displaces all but the Central Control and Thousand Flowers 2050 National Grid mix models, however this is still a clear improvement on the natural gas CHP, which came at an impact cost when the DUKES allocation was compared with these future Grid models.

	Displaced payback period calculated for bio-gas fired power generation using:	
	Bio-gas CHP, Fixed Heat (Bio -gas) Allocation (years)	**Bio-gas CHP, DUKES Allocation (years)**
Nat Gas CHP, Fixed Heat Allocation	33	-
Nat Gas CHP, DUKES Allocation	-	30
UK National Grid 1990, baseline	4	7
UK National Grid 2008	7	13
UK 2050 – Central Control V1.1	17	43
UK 2050 – Market Rules V1.1	10	20
UK 2050 – Thousand Flowers V1.1	14	34

Table 62 Set of displaced impact payback period results for the power generation only of the bio-fuelled CHP (to the nearest year)

9.5.1 SPECIFIC CARBON

Figure 82 compares the specific GWP per unit of power generated by the bio-gas fuelled CHP, using the three allocation method options, with that of the five UK National Grid models. As would be expected given the data already presented, the GWP saving with respect to a natural gas fuelled heat only system is such that the specific GWP is negative when this allocation method is adopted. This implies that the GWP reductions caused by replacing a natural gas heat only system with a bio-gas CHP alone are such that any power generated is 'carbon negative', i.e. would effectively decrease the GWP of the UK electricity mix without even having to displace any previous technology. However, perhaps surprisingly, when either of the other two allocation methods are applied, the power generated by the bio-fuelled CHP still has a higher specific GWP than any estimated for the 2050 UK National Grid mix. This suggests that, unless the most extreme allocation method is adopted, power generated by a heat lead CHP system would not have a place in the future UK decarbonised power supply, whether natural or bio gas fuelled.

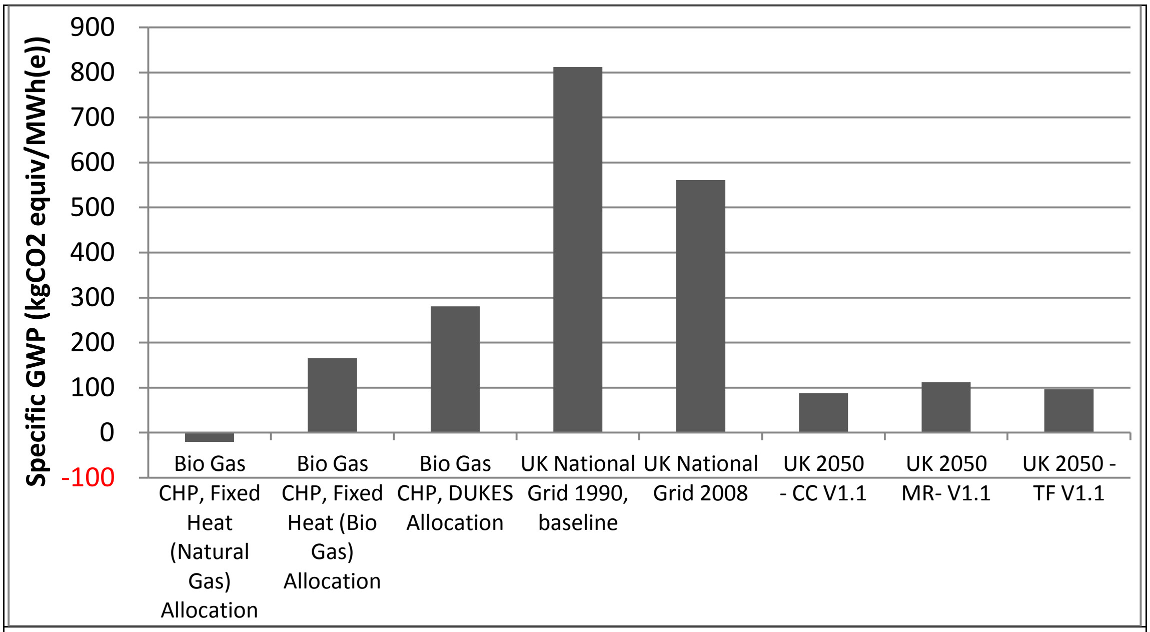

Figure 82 Comparison of specific GWP of the bio-gas fuelled CHP with that of the UK National Grid

Carbon equivalent savings or costs per MWh of generation are estimated against the natural gas fuelled CHP plant and the five National Grid mix models and shown in Table 63. Naturally, because of the negative allocation, when the bio-gas CHP is assumed to replace a natural gas fired heat only system, the GWP saving against any alternative power supply represents over 100%. Most importantly, however, is that even when the 'fixed heat' allocation is applied with reference to a bio-gas heat only system, the GWP saving against the 1990 baseline Grid represent 80% which meets the UK reduction target, showing that CHP and particularly bio-fuelled CHP can make a significant contribution to low carbon power supply in the immediate term, at least. When the DUKES allocation method is applied the fuel switch increases the saving to 65% over the 1990 baseline Grid mix. However, both values for the GWP of the bio-gas fuelled CHP electricity still exceed all future scenario estimates and are generated at a relative carbon cost.

	Bio-gas CHP, Fixed Heat (Natural Gas) Allocation ($kg.CO_2eq/MWh(e)$)	**Bio-gas CHP, Fixed Heat (Bio Gas) Allocation ($kg.CO_2eq/MWh(e)$)**	**Bio-gas CHP, DUKES Allocation ($kg.CO_2eq/MWh(e)$)**
Nat Gas CHP, Fixed Heat Allocation	203	18	-
Nat Gas CHP, DUKES Allocation	-	-	87
UK National Grid 1990, baseline	832	647	532
UK National Grid 2008	580	395	280
UK 2050 – Central Control V1.1	107	-78	-193
UK 2050 – Market Rules V1.1	131	-54	-169
UK 2050 – Thousand Flowers V1.1	116	-69	-184

Table 63 Set of GWP savings and costs per MWh(e) against National Grid mix models

Table 64 presents the displayed carbon payback periods for the two positive power allocation options for the bio-gas CHP model against the two power allocation options for the natural gas CHP and the two National Grid mix models against which a saving is made. Markedly, the bio-gas CHP pays back within or equal to the assumed 30 year lifetime against both the 1990 baseline and 2008 Grid mixes, irrespective of which allocation method is adopted. The bio-gas plant will not payback against the natural gas plant within the plant lifetime which is to be expected as the saving are much smaller but it is important to note that the payback period is shorter than that of the natural gas CHP against the natural gas power only system, see section 8.9.2.1. This suggests that a switch from fossil to bio-gas can have more affect on carbon reduction than fuel efficiency gains available by implementing a CHP system.

	Displaced payback period calculated for bio-gas fired power generation using:	
	Bio-gas CHP, Fixed Heat (Bio-gas) Allocation (years)	Bio-gas CHP, DUKES Allocation (years)
Nat Gas CHP, Fixed Heat Allocation	280	-
Nat Gas CHP, DUKES Allocation	-	97
UK National Grid 1990, baseline	8	16
UK National Grid 2008	13	30

Table 64 Set of displaced carbon payback period results for the power generation only of the bio-fuelled CHP (to the nearest year)

The large discrepancy between the specific GWP and the overall environmental impact of the 2050 UK power supply and the different conclusions this can lead to is striking. This analysis shows how easily overall environmental impact could be increased by decisions made purely in the pursuit of carbon reduction. However, these results also suggests that if the average European power mix manages to decarbonizes in line with the UK then the overall carbon intensity of the reference unit of 'impact per European citizen' will also drop, causing the specific normalized impact score for CHP power, fossil or bio-fulled, to increase in the category of climate change. Perhaps, then, in a future normalized context the overall normalized impact of a CHP system will also exceed that of the UK National Grid, irrespective of allocation method.

9.5.2 SPECIFIC ENERGY

Table 65 shows the specific energy demand per unit of power generated by the bio-gas CHP according to the three allocation method options already described. Clearly, when the demand is allocated via the 'fixed heat' method with reference to a natural gas heat only system the demand from fossil fuels is negative and this value alone renders the overall specific energy allocation negative also. The negative score in the category of non-renewable biomass is negligible when considering the impact per MWh of power. Using the other two allocation methods, the specific fossil fuel demand follows a proportional difference that would be expected, but they are considerably reduced values than those generated for the natural gas CHP model, see section 8.9.3. The gains in the categories of nuclear and renewable biomass are noticeable, particularly when allocated with reference to the natural gas heat only system, although they are not substantial enough to counter the reductions in fossil fuel demand.

Impact category	Unit	Bio-gas CHP, Fixed Heat (Natural Gas) Allocation	Bio-gas CHP, Fixed Heat (Bio-gas) Allocation	Bio-gas CHP, DUKES Allocation
Non renewable, fossil	MJ/MWh(e)	-8 027	879	1553
Non-renewable, nuclear	MJ/MWh(e)	1 028	253	457
Non-renewable, biomass	MJ/MWh(e)	-0	0	0
Renewable, biomass	MJ/MWh(e)	31	8	14

Table 65 Specific energy demand by resource category for the power generated by the bio-gas CHP (to the nearest MJ)

Figure 83 compares the specific energy demand of the power generated by the bio-gas CHP allocated according to the three method options with that of the five National Grid mix models. Importantly, not only is the total specific energy demand of the bio-gas CHP less than the total specific energy demand of all three representation of the 2050 UK National Grid, it is also now less than the isolated specific fossil fuel demand, irrespective of allocation method.

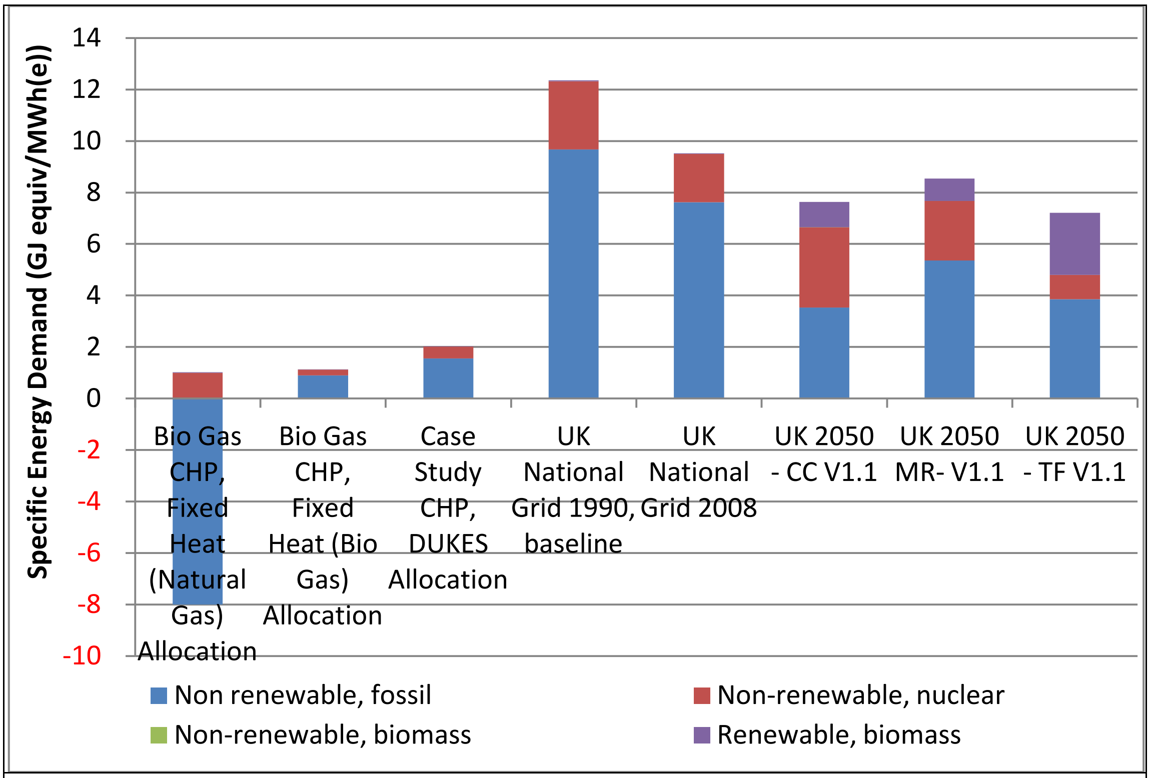

Figure 83 Comparison of specific energy demand of the bio-gas fuelled CHP with that of the UK National Grid

As the bio-gas CHP is again in impact credit from the moment it replaces a natural gas heat only system it is not necessary to calculate any displaced energy payback period using this allocation method. Table 66 presents the displaced energy paybacks for the bio-gas CHP for the remaining two allocation methods. Strikingly, the power generated by the bio-gas CHP is predicted to payback within its 30 year lifetime, irrespective of allocation method is adopted or what alternative power supply it is assumed to displace. Once again the comparative impact differences to the future power supply estimates are in opposition to those identified when GWP is analyzed in isolation.

	Displaced payback period calculated for bio-gas fired power generation using:	
	Bio-gas CHP, Fixed Heat (Bio-gas) Allocation (years)	Bio-gas CHP, DUKES Allocation (years)
Nat Gas CHP, Fixed Heat Allocation	12	-
Nat Gas CHP, DUKES Allocation	-	13
UK National Grid 1990, baseline	3	6
UK National Grid 2008	4	8
UK 2050 – Central Control V1.1	5	11
UK 2050 – Market Rules V1.1	5	9
UK 2050 – Thousand Flowers V1.1	6	12

Table 66 Set of displaced impact payback period results for the power generation only of the bio-fuelled CHP (to the nearest year)

9.6 SUMMARY

The original CHP case study LCA identified that, as would be expected in a fossil fuel generation technology, the operational stage was the most impactful and this was due to the natural gas combustion. To investigate whether a switch to alternative fuels could improve the environmental performance of the CHP plant, particularly with respect to GWP, the LCI of the case study CHP was appropriately adjusted so that the direct fuel demand was met by bio-gas rather than natural gas. The overall impacts improvements available from operating an identical unit on bio-gas derived from waste streams were shown to be substantial, despite some higher impacts identified in some impact categories.

Table 67 summarises the main findings of the case study. The life time energy demand is considerably less than that of the natural gas fired CHP. Significantly, the EGR is above one and the energy payback period is well within the plant design lifetime. These results show that by switching to a bio-gas, CHP units can produce more energy over their lifetime than they consume. The specific impact results, again, show the extreme importance of considering appropriate allocation. Both total normalised impact and the isolated carbon emissions of the bio-gas fuelled CHP system was shown to be less than that of the natural gas fired heat only system. This means that when the impact allocation to the power generated was calculated on the assumption that the later replaces the former, it was found to be impact negative, resulting in an instant carbon benefit against any of the alternative power supplies considered. This also suggests that the merits of simply switching to bio-fuelled heat production rather than a full technology change warrants further investigation, although this is outside the scope of this research. In the context of the low carbon ideal, however, the most important improvement is that even when the specific carbon intensity is allocated with reference to a bio-gas heat only system, the savings against the 1990 baseline Grid mix reaches 80%, which meets the UK reduction target for 2050.

SAVING COMPARED TO NATURAL GAS FUELLED CHP			
Total Normalised Environmental Impact Score			50%
Carbon (equivalent) emissions			24%
Energy Demand			70%
SAVING COMPARED TO SEPARATED GAS FUELLED HEAT AND POWER GENERATION			
		Natural Gas Fuelled Separate Generation	**Bio Gas Fuelled Separate Generation**
Total Normalised Environmental Impact Score		58%	11%
Carbon (equivalent) emissions		39%	16%
Energy Demand		89%	6%
ENERGY ANALYSIS MAIN RESULTS			
Life time energy demand (PJ)	Energy Gain Ratio		Energy Payback period (yrs)
130	2.8		11
CARBON ANALYSIS MAIN RESULT			
Life time carbon emissions (Mt.CO_2eq)			18
	Specific carbon emissions (kg.CO_2eq/MWh))		Displaced Carbon Payback Period (years), against National Grid - baseline(1990)/current (2008)
Bio-gas CHP, Fixed Heat (Natural Gas) Allocation	-20		*Instant*
Bio-gas CHP, Fixed Heat (Bio Gas) Allocation	165		8/13
Bio-gas CHP, DUKES Allocation	281		16/30
POWER ONLY CARBON SAVINGS COMPARED TO NATIONAL GRID			
	Bio-gas CHP, Fixed Heat (Natural Gas) Allocation (kg.CO_2eq/MWh(e))	**Bio-gas CHP, Fixed Heat (Bio Gas) Allocation (kg.CO_2eq/MWh(e))**	**Bio-gas CHP, DUKES Allocation (kg.CO_2eq/MWh(e))**
UK National Grid 1990, baseline	832	647	532
UK National Grid 2008	580	395	280
UK 2050 – Central Control V1.1	107	-78	-193
UK 2050 – Market Rules V1.1	131	-54	-169
UK 2050 – Thousand Flowers V1.1	116	-69	-184

Table 67 Case study improvement analysis: Winnington CHP - summary table of main findings

This study has shown that large overall environmental impact and energy demand savings are available against baseline, current and potential future Grid mixes, particularly with respect to impacts related to fossil fuel consumption. This appears to provide a clear case for bio-gas CHP as a key technology in the pursuit of a low impact, highly electric UK. Perhaps most strikingly, however, the study has shown that even power generated by a bio-fuelled CHP is likely to continue to exceed the GWP of a future decarbonised National Grid. This suggests that, should long term carbon reduction remain the priority of the UK National energy supply, at the potential expense of other environmental concerns and immediate carbon reductions, other low carbon generators should be prioritized over any CHP, irrespective of fuel type, for incorporation into the Grid mix and that alternative and/or additional methods for decarbonising industrial heat should be investigated. However, this would under value the more certain benefits of carbon reductions in short term in favour of remote and hypothetical disbenefits; it is crucial to remember that the prediction that CHP will become a relative carbon burden will only be realised *if* the National Grid supply is decarbonised. Furthermore, the design life of a CHP unit is 30 years so any new units commissioned between now and 2020 would not be in operation by the target year of 2050. With this in mind, the fear of technology 'lock-in' is unjustified. In order to further investigate the role of CHP on the pathway to 2050, rather than just an isolated snapshot of 2050, a discussion within the context of a dynamic future was carried out and is reported in Chapter 10.

CHAPTER 10. IMPLICATIONS FOR UK ENERGY STRATEGY

"A mountain is composed of tiny grains of earth. The ocean is made up of tiny drops of water. Even so, life is but an endless series of little details, actions, speeches, and thoughts. And the consequences whether good or bad of even the least of them are far-reaching"

- Swami Sivanda Saraswati, Hindu spiritual teacher

10.1 IN THIS CHAPTER

The LCA case studies have provided a robust grounding from which to further assess the roles that the technologies could have in and on the pathway to the 'more electric' energy future, as far as 2050. In this chapter, the contribution to carbon and, separately, impact reduction are explained in light of the findings of the LCA case studies. The supply capacities suggested by the Transition Pathway's scenarios are used to explore and better demonstrate the complex and interactive factors that would affect the suitability of these technologies in a, necessarily, dynamic and uncertain future.

10.2 ROLES IN A LOW CARBON ELECTRIC FUTURE

The results discussed in each of the case study sections compared the life cycle carbon emissions per MWh(e) generated with that of the 1990 baseline Grid mix, according to the Transition Pathways study (Hammond, Howard and Jones 2013). Using this comparison, it was shown that the Severn Barrage scheme is capable of achieving a least 90% saving over the baseline, reaching 98% if it is assumed that the operational stage is supplied by a National Grid which is decarbonised to the level of that found in the Transition Pathways Central Control scenario. The savings made available by the case study industrial CHP unit reach 77% which does not reach the 80% target but still is a significant reduction; if the more conservative DUKES allocation method is adopted the saving per MWh(e) still reaches 55%. In Chapter 6 and Chapter 9, the suggested improvements were shown to increase the maximum potential carbon savings to 99% and 80% against the baseline estimate for the Severn Barrage and the CHP unit respectively. In fact, if the power allocation of emissions from the 'improved' CHP unit i.e. a bio-fuelled unit, is calculated relative to a natural gas fuelled heat only unit that it replaces, then the power generated could be assumed to be carbon negative, creating a saving of over 100% per MWh(e).

However, as discussed in section 3.6.4.1, even if the specific emission figures meet or exceed the 80% reduction target, this may not be enough to earn a place in the 2050 low carbon ideal. This was assessed by establishing the percentage proportion of supply each technology could provide at what percentage proportion of ideal carbon emissions.

10.2.1 SEVERN BARRAGE

It is estimated that the Severn Barrage scheme would generate 17TWh per year, which has been predicted to constitute 4% of the total UK energy supply (Severn Tidal Power Group and the Department of Energy 1989). 17TWh is around 3%-4% of the potential supply capacity in 2050, according to the Transition Pathways scenarios. Hence in order to assess whether the scheme is appropriate in the 2050 decarbonised ideal, the life time carbon per year must be compared to 3% of the ideal 2050 power supply emissions. Using the reported emission figures, the target carbon emission per year for the Severn Barrage scheme, to 1 significant figure, is given by:

$$3\% \times 41\ Mt.CO_2eq = 1\ Mt.CO_2eq$$

Using the life cycle emission estimate, the target carbon emission per year for the Severn Barrage scheme, to 1 significant figure, is given by:

$$3\% \times 49\ Mt.CO_2eq = 2\ Mt.CO_2eq$$

The life cycle carbon emissions per year for the primary model of the Severn Barrage scheme, to 1 significant figure, is given by:

$$\frac{120\ Mt.CO_2eq}{120\ years} = 1\ Mt.CO_2eq$$

This result already confirms that the Severn Barrage would be able to contribute to the ideal low carbon 2050 Grid mix, irrespective of which target is adopted. However, the magnitude of the contribution is likely to be even better than this implies. As reported in Chapter 5, the main contributor to the overall impact of the Severn Barrage plant is electricity drawn from the National Grid, so when making comparisons with the overall UK supply it is fair to use the plant representation which is based on the same network mix. Assuming that the electricity is supplied by the least carbon intensive Grid representation, i.e. the 'Central Control' scenario result taken from the Transition Pathways work, the carbon emissions per year of life for the Severn Barrage scheme fall well below the target carbon emission per year, and are calculated, to 1 significant figure, thus:

$$\frac{27\ Mt.CO_2eq}{120\ years} = 0.2\ Mt.CO_2eq$$

10.2.1.1 Improved Severn Barrage: Without 'flood pumping'

The lifetime carbon emissions per year for the primary model of the Severn Barrage scheme assuming ebb generation only, to 1 significant figure, is given by:

$$\frac{21\ Mt.CO_2eq}{120\ years} = 0.2\ Mt.CO_2eq$$

This figure already falls well below the carbon target for 3% of UK electricity supply emissions in 2050. Assuming that the electricity is supplied by the least carbon intensive Grid representation, i.e. the Transition Pathways 'Central Control' scenario, the lifetime carbon emissions per year for the Severn Barrage scheme assuming ebb generation only, to 1 significant figure, is given by:

$$\frac{11\ Mt.CO_2eq}{120\ years} = 0.1\ Mt.CO_2eq$$

It has been shown that, given reasonable assumptions, the Severn Barrage can make a significant contribution to meeting the UK carbon reduction target of 80% below 1990 levels by 2050. In short, the Severn Barrage could provide 3-4% of the UK 2050 electricity supply capacity at around 0.5-2% of either target set for power sector emissions in 2050 even if 'flood pumping' is still employed, and around 0.2-0.4% if the plant operates in ebb generation only.

10.2.1.2 Further UK wide tidal barrage application

Whilst the Severn Barrage has been used as a case study, it is proposed that the results can be taken as an indicative measure of the performance of any proposed barrage both nationally and internationally. In section 4.4.1 it was estimated that the annual potential electricity supply capacity from the UK tidal range resource was 110 TWh. This would constitute 22-28% of the 2050 total UK electricity supply, as suggested by the Transition Pathways scenarios(Hammond, Howard and Jones 2013). It has been assumed that this supply capacity could be harnessed via barrage schemes identical to the design adopted in the Severn Barrage case study, in order to examine the potential role of UK wide tidal range development. It is of course extremely unlikely that development on this scale could possibly take place by 2050, it is after all, still very uncertain whether the Severn Barrage scheme alone will be implemented. The marine power capacity in the Transition Pathways' scenarios certainly does not reach this magnitude. It is, however, instructive to undertake this final exploratory calculation to give a full picture of the potential of tidal range power in the UK energy future.

Operation in ebb generation only mode slightly reduces output, so the UK supply capacity, if no scheme uses 'flood pumping', is estimated at 103 TWh, using the same proportional reduction of 16TWh from 17 TWh implied by the data found for the Severn Barrage scheme (Severn Tidal Power Group and the Department of Energy 1989). This would represent 21-27% of the 2050 supply. 21% of the target emissions for the electricity supply sector in 2050 is 8 Mt.CO_2 based on reported figures and 10 Mt.CO_2 based on the life cycle estimate. Assuming that electricity supply is proportional to carbon emissions, the annual emissions that could arise from UK wide tidal range development all fall below these targets, and are shown in Table 68.

	Annual (life time) carbon emissions, depending on operational mode (Mt.CO_2)	
Grid supply carbon intensity equivalent to:	'Flood pumping' employed	Ebb generation only
UK National Grid 2008	6	1
UK 2050 – Central Control V1.1	2	1

Table 68 GWP per year of UK wide tidal barrage development for electricity generation

So the estimated electricity supply from UK wide tidal barrage development would provide 21-28% of the UK total supply capacity whilst only contributing 1-16% of the target carbon emissions in the year 2050, dependant on operational mode and carbon intensity of the Grid mix supplying the installations.

10.2.2 INDUSTRIAL CHP

The case study CHP is an existing plant. The electricity resource option under scrutiny is the UK wide role out of additional industrial CHP systems to replace currently operating heat only systems, rather than the case study CHP itself. Hence, when assessing the potential contribution to the carbon reduction targets it makes sense to only look at the currently under exploited industrial heat resource, across the UK. The results of the case study were used to estimate the additional generation potential available and the likely carbon emissions from UK wide exploitation of industrial heat for CHP via a simple proportional increase. In the case of the studied CHP scheme an annual heat load of 2450

GWh(th) leads to a generation of 911 GWh(e). Applying this ratio, the UK remaining annual industrial heat load of 110 TWh(th), as estimated in section 7.6, could lead to an power capacity of 41 TWh(e). This very close to the figure extrapolated from the reported capacity increases (Her Majesty's Government 2012, DUKES. Table 7.8) of 42 TWh(e), as discussed section 7.6, so can be taken as a reasonable working figure. 41 TWh(e) represents 8-11% of the of the 2050 total UK electricity supply, as suggested by the Transition Pathways scenarios.

Using the reported emission figures, the 2050 target carbon emission per year for the power provided by exploiting the remaining industrial heat load via CHP conversion, to 1 significant figure, is given by:

$$8\% \times 41\ Mt.CO_2eq = 3\ Mt.CO_2eq$$

Using the life cycle emission estimate, the 2050 target carbon emission per year for industrial CHP conversion, to 1 significant figure, is given by:

$$8\% \times 49\ Mt.CO_2eq = 4\ Mt.CO_2eq$$

First, it was assumed that the remaining heat resource is currently being entirely provided by natural gas fired heat only systems. If these systems are replaced by gas fired CHP then the specific lifetime carbon emission allocation to the power generated would be 183 or 367 kg.CO_2eq/MWh, dependant on whether the 'fixed heat' or DUKES allocation method is adopted. This gives an annual emission allocation for the total power available from complete industrial CHP conversion of 8 or 15 Mt.CO_2, dependant on allocation method. Both these figures are greater than the target. Table 69 shows the percentage of the 2050 emission target for the power sector that these emissions could constitute, dependant on the target and allocation method adopted.

	Percentage of target emissions calculated using:	
Target implied by:	'Fixed Heat' Allocation	DUKES Allocation
Reported emissions	18%	37%
Life cycle emissions	15%	31%

Table 69 Percentage proportion of the 2050 emission target that further industrial CHP roll out would contribute

These results further confirm that natural gas fired CHP could not make a positive contribution to the UK low carbon ideal in 2050. It is no real surprise that this result is over the target as the case study results interpretation have shown that the specific emission savings for power from industrial gas fired CHP fall short of even the 80% reduction target for 2050.

Figure 84 compares the carbon intensity of the Transition Pathways Grid mixes with that of the estimates for the CHP case study. All carbon estimates for the CHP system exceed the Transition Pathways Grid intensity by 2035. As might be expected, if the DUKES allocation method is adopted the CHP system falls behind the National Grid mix earlier than if the 'fixed steam' allocation is adopted. The natural gas fired systems become a carbon burden earlier than a bio-gas fuelled system, using the equivalent allocation method. Most importantly, it can be seen that all estimates for industrial CHP provide a carbon reduction reletive to all scenario mixes at least until around 2027.

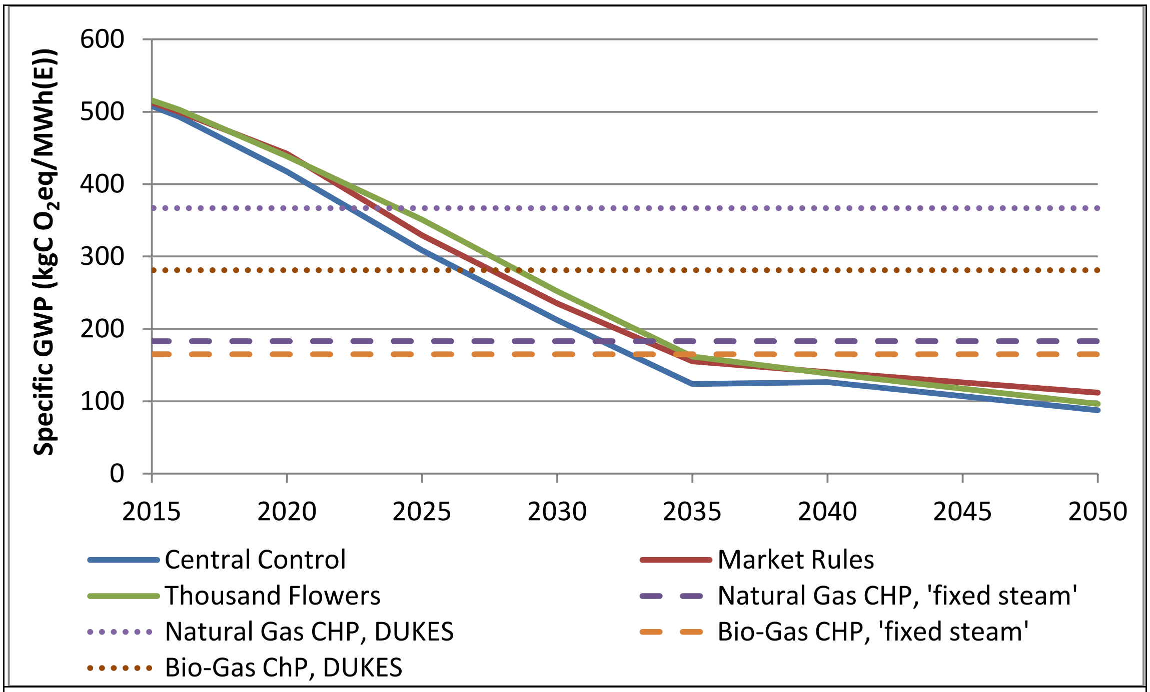

Figure 84 Comparison of the specific GWP for the three Transition Pathway Grid mixes over time to 2050 with that of the various estimates of the case study CHP

The specific emission benefits of industrial CHP are available now. Furthermore, as a CHP unit has a design life of 30 years, any units commissioned before 2020, so including any new installations in the next 6-7 years, would cease operation before 2050 anyway. Hence, it is more instructive to compare supply capacity and emissions with more contemporary data.

In 2008, the UK electricity supply reached a total of 400 TWh(e) (Her Majesty's Government 2012, DUKES. Table 5.2), in the same year, reported emissions for UK power stations were 174 Mt.CO_2 (equivalent) (Office for National Statistics 2013, UK Emission Statistics. Table 3). Life cycle emissions for National Grid power supply can be estimated at 224 Mt.CO_2 (equivalent), using the specific emission figure for 2008 provided by the Transition Pathways work, shown in Table 2 of this thesis. Hence, further industrial CHP conversion, assuming gas fired systems, could have provided 10% of the 2008 UK electricity supply while only releasing 4-9% of the reported emissions and 3-7% of the life cycle emissions, depending on allocation method.

The available heat load was calculated using data for 2010. A life cycle emission estimate for the UK National Grid is not available for that year. However, for completeness, the reported emission figure for that year is 157 Mt.CO_2 (equivalent) (Office for National Statistics 2013, UK Emission Statistics. Table 3) and the supply capacity reached 384 TWh (Her Majesty's Government 2012, DUKES. Table 5.2). Hence, the remaining industrial heat load resource could have provided 11% of the power supply at 5% or 10% of the emissions in 2010, dependant on allocation method and assuming natural gas fired systems.

In fact, the amount of industrial heat provided by natural gas in 2010 reached only 105 TWh(th). Much of this was provided by existing natural gas fired CHPs, but even if all of that gas fired heat was provided by heat only systems, that still leaves 5 TWh(th) of non-CHP generated heat that was provided by other fuels. So it can be assumed that at least 5

TWh of the remaining industrial load is provided by more carbon intense fuels than natural gas, such oil and coal. Using the 'fixed heat' allocation, the specific emissions of power generated by a natural gas CHP that replaces an oil or coal heat only system would be extremely low. Hence, the emissions allocated to power generated by even natural gas fuelled CHP systems that exploit the remaining UK industrial heat load are actually likely to be much lower than those calculated here, when the 'fixed heat' allocation is adopted.

Figure 84 also implies that even if the National Grid actually decarbonises in step with the Transition Pathways' scenarios, the carbon benefits of schemes commissioned today would outweigh any carbon costs incurred before the end of their 30 year design life. The benefits of reducing carbon emissions today should not be underestimated. Accelerated and irreversible climate change could be the consequences of a failure to do so. The mechanisms of carbon feedback loops are well documented in climate science. Hence, delaying carbon reductions now could have a greater impact on the atmospheric carbon content of the future than any future technology Grid mix that could be conceived.

10.2.2.1 Improved Case Study CHP: Bio-Fuel

If it is assumed that 41 TWh(e) of power is provided by bio-gas fuelled CHP systems that replace bio-gas fuelled heat only systems, the associated life cycle emissions would be 7 Mt.CO_2 (equivalent) or 12 Mt.CO_2 (equivalent) using the 'fixed heat' or DUKES allocation method respectively. These values are still greater than the 3 and 4 Mt.CO_2 targets set and would constitute 16% or 28% of the 2050 emission target implied by reported figures and 14% or 24% of that implied by the life cycle estimate. This shows that even though the specific emissions of power generated by bio-gas fuelled CHP could achieve a saving of 80% against the 1990 baseline, this is not enough to earn it a positive role in the 2050 low carbon, more electric future, using these allocation methods.

Compared to 2008, bio-fuelled CHP could have provided 10% of the supply at 4% or 7% of the reported emissions and 3% or 5% of the life cycle emission estimate, dependant on allocation method. Compared to 2010, 11% of the supply could have been provided also at 4% or 7% of the reported emissions, dependant on allocation method. This further confirms the benefit that conversion to CHP can offer emission reduction today, particularly from bio-gas fuelled systems.

In fact, in 2010 only 6 TWh(th) of industrial heat was provided by bio-energy or energy from waste systems (Her Majesty's Government 2012, Energy Consumption in the UK. Table 1.14). It is likely that most of this bio-fuelled heat supply came from existing CHP systems, but even if it is assumed that it is fully available for CHP conversion, that still leaves 104 TWh(th) of heat that is currently provided by natural gas or other more carbon intense fuels, such as oil or coal that could be converted to bio-gas fuelled CHP. It was established that if it is assumed that a natural gas fired heat only system is replaced with a bio-gas fuelled CHP system and the 'fixed heat' allocation method is applied, then the power generated is actually carbon negative. Although it seems that even bio-fuelled CHP plants would not have a place in the UK 2050 carbon ideal , the significant carbon benefits they can offer over current industrial heat production methods today should not be over shadowed.

10.3 ROLES IN A LOW IMPACT ELECTRIC FUTURE

The case studies assessed each technology's performance in a wide range of environmental impacts rather than just carbon intensity. The results highlight the consequences of focusing on one environmental impact over any other, in this case carbon emissions. There are currently no targets set for reducing any other environmental impact other than carbon emissions. This makes it harder to assess the quantitative role any given technology would earn in a more sustainable future, in the way that it has been possible to do so with respect to the ideal low carbon ideal in section 10.2. This should not, however, become an excuse to become blinkered in the light of such firm carbon reduction targets.

The Severn Barrage demonstrated a better environmental performance than any National Grid mix considered, in every impact category assessed. The Barrage is a renewable technology so could also contribute to the renewable energy target, to meet 15% of the UK demand with renewable energy (Her Majesty's Government 2011, UK Renewable Energy Roadmap. pp 9.). However, the assessment does not account for the ecological impacts which have been consistently raised as an objection to its construction. The determination of the significance of these impacts surely lies in a thorough comparison of those arising as a result of the Barrage construction and those arising from the equivalent power capacity provided by the National Grid, in line with the comparison analysis carried out in this research. However, ecological impacts of the type predicted to result from the Barrage construction, are highly specialized and outside the scope of this research. They are not even likely to be included in the emerging LCSA methodology, as mentioned in Chapter 3.

In contrast to the Severn Barrage, industrial CHP conversion, whose relative carbon merit has been shown to be much more variable, has no such obvious ecological objection. If the systems were run on bio-fuels derived from energy crops, then the issue of ecological impacts would surely arise, however this study has assumed that the bio-gas could be provided by organic waste and sewage sludge. The injection of substantial amounts of gas for such sources into the national gas grid for combustion is being seriously considered (National Grid 2009) and is seen as *solving* the ecological problem of disposing of the waste which humans are already producing (Institution of Mechanical Engineers 2006).

An important finding is that of the performance of the CHP system, whether natural gas or bio-gas fuelled, in the full range of impact categories assessed. Despite falling short of the carbon intensity level set by the Transition Pathways National Grid models for 2050, the bio-gas fuelled unit out performs all National Grids mix considered, irrespective of allocation method adopted, in all other categories. The natural gas unit out performs all other 2050 National Grid mixes in nearly all categories, only falling short of the Central Co-ordination and Thousand Flowers mixes in the category of fossil fuel depletion. This is a substantial result. What is most revealing is that the natural gas unit out performs the Market Rules Grid mix for 2050, irrespective of allocation method. This is because of the proportion of power that is supplied by CCS units in the Market Rules scenario. CCS technologies achieve low carbon emissions but have the potential for high impact costs in the other categories assessed, hence they demonstrate the possible dangers of focusing on only one category. When the 'fixed steam' allocation method is adopted, the natural gas CHP actually does so well in the remaining impact categories that the total normalized impact score is less than any of the 2050 Grid mixes. This is despite the poor scores in climate change and fossil fuel depletion, Figure 73.

Figure 85 compares the changes in total specific normalised environmental impact score for the three Transition Pathway Grid mixes over time to 2050 with that of the various estimates of the case study CHP. It can be seen that all CHP estimates fall below the the

Market Rules mix, and all but the the instance where the DUKES allocation method is applied to the natural gas fired system, fall below all the Grid mixes for the full timeframe considered. If the DUKES allocation is adopted, the specific impact of the natural gas fired system will exceed that of the Central Co-ordination mix around 2028 and the Thousand Flowers mix around 2035. What is most telling about this graph, is that the specific impact of the Market Rules and Central Co-ordination mixes reach their minimum value in 2035 and then big to climb up. In fact, it looks as though the trend in the Central Co-ordination mix could cause it to exceed even the DUKES estimate for natural gas fired CHP sometime after 2050. This upward trend is due to the increases in CCS implimentaion from 2040 onwards. As already discussed, CCS is a low carbon technology but not a low impact one. The comparative result shown here demonstrates that technologies that perform well in a number of areas of environmental concern, such as CHP, should not be rejected in favour of technologies that perform exceptionally in the single category that is currently prioritised.

Furthermore, the implementation of technology that can use fossil fuels more efficiently should not be rejected in favour of waiting for a renewable, or even nuclear solution, that is still heavily influenced by controversial opinions of the public and the Government. This will surely lead to the continued inefficient use of fossil fuels and the maximisation of the resource depletion and toxicity impacts that are associated with doing so.

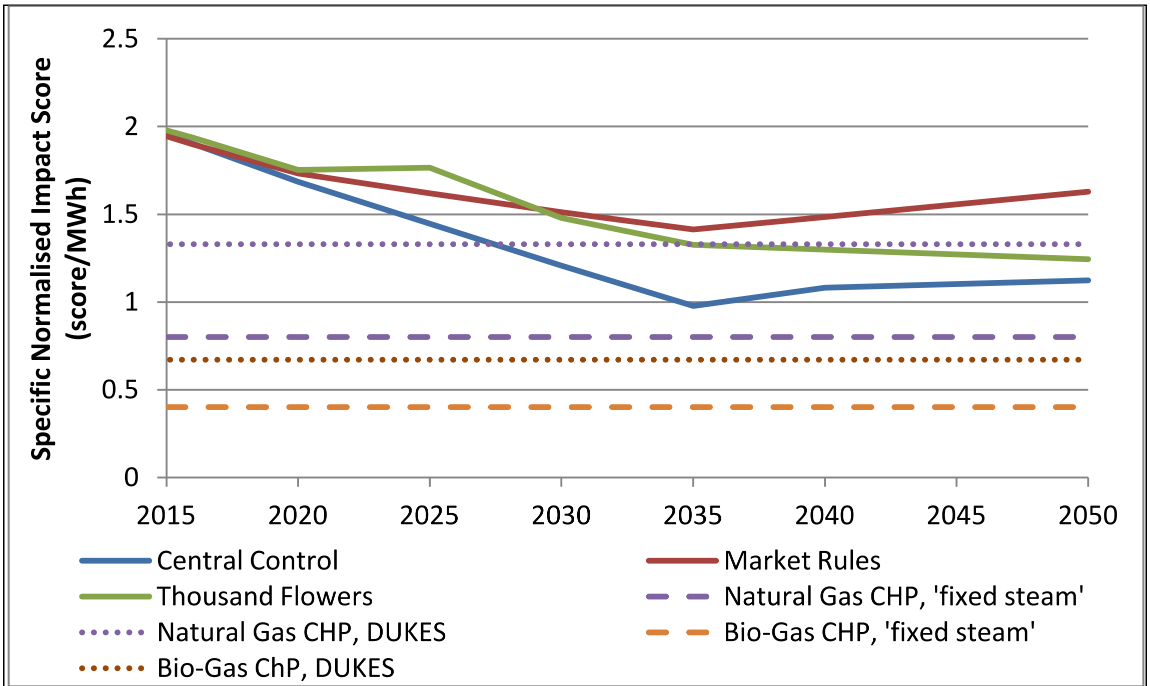

Figure 85 Comparison of the specific normalised environmental impact score for the three Transition Pathway Grid mixes over time to 2050 with that of the various estimates of the case study CHP

10.4 ROLES ON THE TRANSITION PATHWAY

In order to better inform the next stages of the Transition Pathways project, the Transition Pathways scenarios were examined in the context of the greater understanding made available by the LCA case studies. This process also served to compare the technologies further and better understand their roles on the dynamic pathway to2050

10.4.1 MARINE POWER IN THE TRANSITION PATHWAYS

In all scenarios, supply capacity from marine power does not make a contribution to the Grid mix before 2020. According to the scenario versions 1.1, capacity peaks by 2035 in Market Rules and Central Control, reaching 22 TWh and 24 TWh respectively, and by 2040 in Thousand Flowers, reaching 24 TWh. In all cases, once the peak capacity is reached it is maintained through to 2050. These figures are well within the predicted limits of the UK marine resource; however it is unclear whether these figures are within the predictable limits of technical feasibility. In all scenarios, however, if the Barrage is not in place by 2035 it will leave a large technology gap in the Transition Pathways supply capacity that will have to be filled by less developed and much lower rated technology options.

The Severn estuary is the largest single marine resource in UK waters at a capacity 17 TWh per year. The Barrage proposal has a long history in UK energy policy, as is explained in section 4.5 but a final decision on whether or not a barrage will ever be built has yet to be reached. The announcement of final design proposal, let alone a date for construction to begin, still seems remote. What recent developments have shown is that the Barrage's best hope of construction lies with private investment, so it seems most likely to be implemented if the UK socio-economic landscape develops along the lines of the Market Rules scenario. Action from any private company is currently waiting on the go ahead from government which is undertaking a public consultation, inviting evidence and opinion from the general population. So, as far as can be seen, it is not the market that is delaying construction. It would seem that, unless there is a significant shift in priorities, the Severn Barrage would not be a likely technology in a Central Co-ordination or Thousand Flowers scenario.

10.4.2 CHP IN THE TRANSITION PATHWAYS

According to the scenario versions 1.1, the total electricity supply from CHP schemes in 2050, is 52 TWh(e) for the Market Rules and Central Coordination scenarios and 88 TWh(e) in the Thousand Flowers scenario. Total CHP supply capacity increases over time towards 2050 in all scenarios, but this is only due to increases in bio-fuelled systems. The highest proportion of supply is from renewable fuelled CHP schemes; 25 TWh(e) in the Market Rules and Central Control scenarios and 61 TWh(e) in Thousand Flowers, in all scenarios this supply capacity is only reached in 2050. In all scenarios, fossil fuelled CHP capacity either remains constant from the current amount or drops to nil by 2016. In all scenarios, 22 TWh(e) of electricity is supplied by natural gas fired CHP schemes (Transition Pathways: Technical Elaboration Working Group 2010), and in all scenarios this supply capacity is reached by 2012 and then remains constant.

It may seem that, by definition, widespread industrial CHP is most likely to be implemented in a Market Rules type socio-economic future. However, recent history has shown that the slow uptake of CHP to date can be accredited to poor government incentives; see section 7.3, so it follows that a Central Co-ordination scenario could have the most influence on increased CHP penetration. The Thousand Flowers scenario sees a large increase in CHP for domestic heat, which would not immediately imply any change in industry; however it seems likely that widespread understanding and acceptance of the technology would lead to an increase in all sectors. Further to this, consumer participation will be essential to generating suitable bio-gas feed stocks, as discussed in section 7.7.1. In short, further industrial CHP seems compatible with all scenarios.

The scenario supply spreadsheets do not expressly split the supply capacity by sector. However, a significant proportion of the CHP capacity in the Thousand Flowers scenario is in the form of district heating systems and domestic micro-CHP. Hence, it must be assumed that industrial CHP capacity does not, in any scenario, reach the 66 TWh(e) limit extrapolated from the reported capacity increases (Her Majesty's Government 2012, DUKES. Table 7.8), as discussed, nor the 65 TWh(e) maximum capacity determined by this work. In 2010, 89% of the power supplied by the UK CHP stock was from the industrial sector (Her Majesty's Government 2012, DUKES. Table 7.8) so, for simplicities sake, it is assumed that the industrial CHP power supply capacity in each scenario is 89% of the of the total CHP capacity in the Market Rules and Central Control scenarios, reaching 46 TWh(e) in 2050. It has also been assumed that 24 TWh of the 2010 CHP power supply capacity, which is the value actually reported for that year (Her Majesty's Government 2012, DUKES. Table 7.8), is provided by units commissioned in 2000, in line with the case study scheme and any additional capacity in 2010 is provided by units commissioned in that year. These assumptions are required in order to make estimates of when units would be decommissioned and hence, need replacing.

10.4.3 TIMELINE FOR TECHNOLOGIES

Figure 86 visualizes the development of each of the studied technologies up until 2050 according to the Transition Pathways scenarios and hence, one way that the two could participate in the UK energy future.

The Severn Barrage is shown to provide 17 TWh of low carbon and low impact power supply from 2035 onwards, as the marine capacity in all scenarios implies that it would be online by this time. 2035 also marks the point in the future at which CHP ceases to provide a relative carbon benefit within the context of the Transition Pathways scenarios, but this could happen anytime between 2027 and 2035. Commissioning the Severn Barrage would cause a reduction to the impact of the overall Grid mix, so it follows that it would coincide with the point that CHP becomes a carbon burden.

The Severn Barrage case study revealed that its largest contribution to overall impact would be from the National Grid itself, which would meet electricity demand outside of generating hours. So reducing the impact and carbon intensity of the Grid mix becomes essential to reducing that of the power from the Barrage, as well as a goal in itself. This would seem to make the argument for reducing CHP capacity more compelling, in fact, it could mean the opposite. The decision as to whether CHP supply capacity should be maintained and/or increased must also be made relative to the technology that would fill the gap that CHP would be leave behind. If the National technology development, whether public or private, is in the midst of a project on the scale of the Barrage, it seems unlikely that enough other similarly low impact schemes could be simultaneously implemented, as to replace the CHP capacity. Hence, maintaining the CHP stock would still be the best thing to do in order to keep Grid carbon intensity, inclusive of the Barrage supply, to its minimum.

The risk of so called, technology ‘lock-in’ has been defined as committing future generations to high carbon emissions by commissioning plants that look good now but will become a burden relative to a decarbonised National Grid. A decision to commission the Severn Barrage would indicate a significant shift in attitude towards the need for renewable energy, i.e. that it is of a higher priority than financial and ecological costs, so it would seem equally possible that its construction could be preceded or quickly followed by other large scale renewable developments. If this were the case then a CHP 'lock-in' could result. However, Figure 86 helps to illustrate that the short design life the CHP means that there would be opportunities in the future to minimise the likelihood and/or consequences of a CHP 'lock-in'. The number of CHP units, of equivalent rating to the case study unit, that would be required to meet the industrial CHP capacity is shown at 10 year intervals up to 2050. Around 27-32 new units would need to be commissioned around 2030 in order replace the CHP stock that has reached its end of life whilst maintaining the required supply capacity. This is the largest number of units required at any one interval up to 2030. It also falls in the window that has been predicted to be the point at which CHP might switch from being a carbon benefit to be a carbon burden. A thorough review of the carbon benefit of a CHP unit relative to the current Grid and the probable Grid of the immediate future could be undertaken before any new or replacement schemes are commissioned.

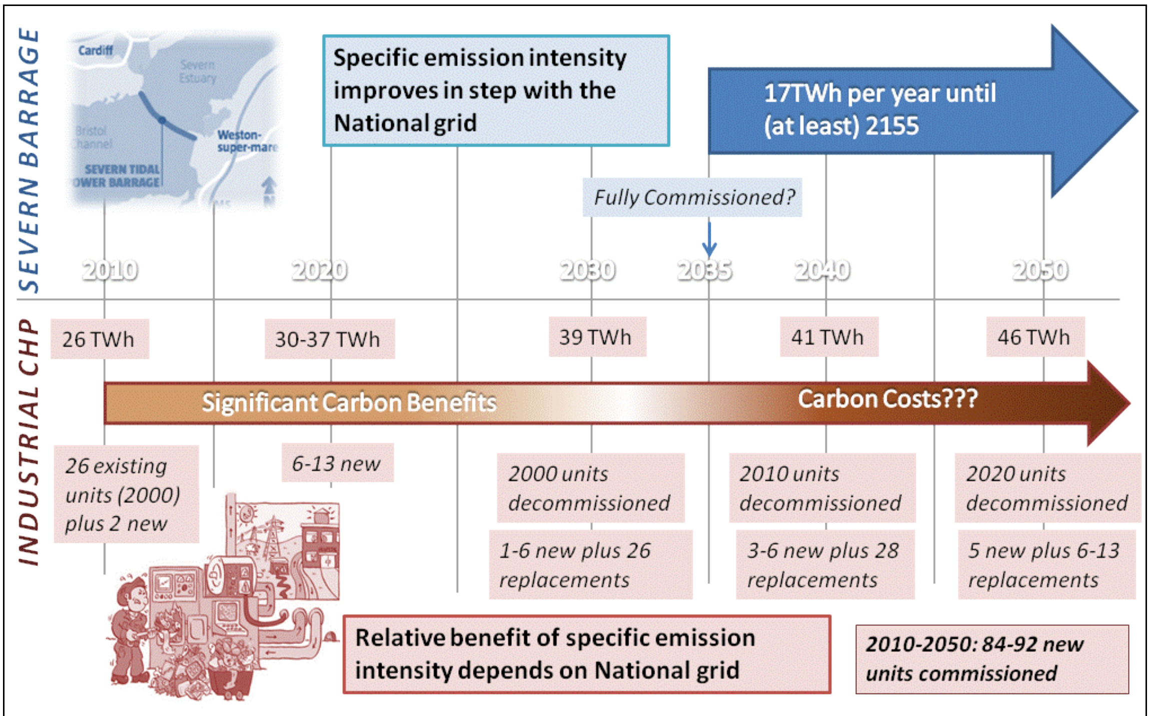

Figure 86 Timeline showing the roles of the case studied energy systems on the 'Transition Pathway' to 2050

10.5 ROLES IN THE UK ENERGY POLICY

If the benefits of both schemes identified by the LCA case studies do nothing else, they highlight the opportunities missed in the last 100 years. What predictions can be made about the influence of this work on the actually energy strategy for the UK?

This Severn Barrage study has provided a much more thorough environmental assessment than any previously carried out, and than any which have been used by the government to make previous policy decisions. Most importantly it has shown that the impact of the operation stage should not be ignored, and this has lead to the identification that the benefits of 'flood pumping' are far outweighed by the additional impacts. Overall the study has shown that the Severn Barrage performs well in terms of environmental impact and would make a significant beneficial contribution to achieving the UK carbon reduction and renewable energy targets. This was, however, already shown by the existing energy and carbon analyses of the scheme, as reviewed in section 4.7. This study actually shows the Severn Barrage to have a worse carbon energy footprint than previously identified because of the more realistic analysis of the operational inventory. This is, then, evidence that it is not the anticipated environmental performance that is delaying, or will yet prevent, the construction of the plant. The ecological concerns are a contributory factor but this still is not the main cause of inaction. The analysis of the governmental report in 2010, see section 4.5.1 shows that downfall of the Severn Barrage is the substantial capital cost and the long lead time. Any likely government will strongly resist undertaking the former when the later is likely to prevent completion, and therefore any return, within the term of same government. A private consortium would seem more likely to take these constraints in its stride. However, the fear that private development of the site could lead to a financial burden rather than a legacy for the public, as prophesised by the now disbanded SDC (Sustainable Development Commission 2007), renders this a less than appealing prospect. Until the UK has a government that is more committed to real sustainability rather than high impact activities that fit conveniently within their elected term, it seems that there will not be even a satisfactory decision on the Barrage, one way or the other.

The above discussion has shown that although CHP might not make a direct contribution to achieving the 2050 ideal decarbonised Grid, the role it can play along the pathway towards 2050 is important and complex. Until there is sufficient renewable energy, or perhaps nuclear, capacity to compete with that which could be provided by harnessing the existing industrial heat load, industrial CHP conversion should be implemented without fear of a carbon 'lock-in'. Decarbonisation based on widespread implementation of CCS technology should not prevent the implementation of industrial CHP as this would lead to the exacerbation of other environmental impacts, particularly fossil fuel depletion.

This finding alone is unlikely to be sufficient to bring about a widespread uptake of CHP in industry. History has shown that the decision to commission a CHP unit mainly relies on the economic conditions of the 'spark spread' and government incentives, the latter having to compensate for the former if required. If energy strategy were to focus on bringing substantial renewable and nuclear power schemes on line, it is possible to imagine a situation where the price of primary fuels, particularly natural gas, increased significantly compared to the price of electricity. This could mean that the 'spark spread' would make maintaining, let alone increasing, the CHP stock unviable before its relative carbon intensity did. If the carbon and impact benefit of continued CHP was still relevant, then further subsidies or perhaps carbon tax relief would have to be introduced. It seems unlikely that this would happen smoothly, as the subsidising of a fossil fuel technology in a renewable and nuclear powered future will seem a step backwards. These concerns are, however, unlikely to be applicable to bio-fuelled schemes. Although the combustion of bio-fuels still has an associated carbon emission, the carbon benefits of replacing fossil fuels are more generally understood so could probably be incentivised more easily. Furthermore, as discussed in section 7.7, schemes that use bio-fuels derived from waste streams should be encouraged as they deal with the dual aims of generating low impact power and waste disposal. These schemes would not suffer from an increasing 'spark spread' because as the cost of traditional waste disposal increases, which is already being seen in increased landfill taxes, bio-fuelled CHP schemes should be able to obtain waste based fuels for very little or even actually charge. It is possible that environmental taxes on transport fuels, particularly aircraft fuel, could lead to enough competition for bio-fuels that the issue of the 'spark spread' becomes relevant to even a waste based feedstock, however the scale of technology change required for this to become a reality seems remote. In short, it seems that bio-fuelled CHP has the most promising future in UK energy policy.

10.6 SUMMARY

Assessing the roles that the case study technology could actually play in the ideal 2050 National Grid mix, is more complicated than calculating the specific saving available against the 1990 baseline Grid, as was done in the Results Interpretation sections in of the case study chapters. This is because it is anticipated that the 2050 supply mix will not only have to have an emission intensity that betters the reduction target because it will also have to meet an increased demand. It was shown that the carbon benefit of the Severn Barrage in the 2050 ideal was assured, contributing at least 3% of the 2050 power supply at only 0.5-2% of the ideal emissions if 'flood pumping' was employed or only 0.2-0.4% of ideal emissions if 'flood pumping' were excluded from the operational mode. It was also shown that development of the UK wide available tidal range resource could result in at least 21% of the 2050 supply whilst contributing only 1-16% of the ideal emissions, depending on operational mode and power supply. The percentage contribution to carbon emission from industrial CHP was shown to exceed that of the percentage supply contribution in 2050 in all instances, bar one. As was determined in Chapter 9, when the 'fixed heat' allocation method is used, i.e. the allocation of the emissions to the power supply is made relative to the heat system that the CHP replaces, a bio-gas fuelled CHP that replaces a natural gas fired heat only system would generate carbon negative power. Given that at least 104 TWh(th) of the 110 TWh(th) of industrial heat load identified as available for CHP conversion, if not all, is currently supplied by natural gas, coal and oil, then implementation of widespread bio-gas fuelled industrial CHP has greater carbon reduction potential than even the Severn Barrage. It was calculated that harnessing the 2010 available industrial heat load could have provided 11% of the power supply at a maximum of 10% of the emissions in the same year, even if natural gas units were assumed. Given that the 30 year design life of a unit would prevent any system installed before 2020 from operating in 2050, this is a more relevant result. Perhaps most importantly, the fact that reducing carbon emissions today is essential to preventing positive carbon feedback loops being established, commissioning further CHP now would still help reduce atmospheric carbon levels in 2050, even if today's new units become a relative carbon burden before their end of life. The Severn Barrage performed well in the LCA across all impact categories but attention was drawn to the fact that the perceived ecological impacts of the scheme were not included in the study and that further work with respect to this would be required before a conclusion could be reached as to the true impact of the Barrage. Conversely, the only impact identified that industrial CHP could have outside those assessed in the case study would be a beneficial one with regard to responsible waste disposal if suitable bio-fuelled schemes were implemented. CHP performed well in the categories assessed and was shown to have a lower specific impact than that of the Transition Pathways' Grid mixes for the full period from now until 2050 in most cases. This shows that technologies that perform well in a number of areas of environmental concern, such as CHP, should not be rejected in favour of technologies that perform exceptionally in the single category that is currently prioritised, such as CCS.

The relationship that the two studied technologies have with the remaining Grid mix and with each other on the pathway way to 2050 is complex. The commissioning of the Severn Barrage may reduce the specific carbon intensity of the National Grid sufficiently, so that it marks the point that CHP becomes a relative carbon burden. However because the carbon intensity of power from the Barrage is reliant on that of the National Grid mix, further CHP implementation should only be stopped if there is a suitable low carbon *and* low impact alternative that can fill the capacity gap that would be left. There are reasons why development of the Severn estuary would make the simultaneous implementation of other large renewable schemes more as well as less likely. Either way, it was proposed that the 30 year design life of CHP units is short enough as to limit the consequences of a technology 'lock-in'. Specifically bio-gas fuelled industrial CHP systems where the gas has been derived from waste streams has been identified as the most important technology, of those assessed, on the road to a more sustainable energy future for the UK. This is because of the carbon and impact savings that it can make against current industrial heat production, the current National Grid mix and even against the Transition Pathways Grid mixes in and as they evolve to, 2050. Schemes of this kind also seem the most feasible as they also address the problem of the provision of an economically competitive fuel via the economically valuable service of responsible waste disposal.

CHAPTER 11. CONCLUSION

In 2008, the UK Government enforced the target to reduce the UK carbon account for the year 2050 to at least 80% less than the 1990 baseline (Her Majesty's Government 2008, Climate Change Act. Part 1.). In order to meet this ambitious target it is widely thought that the UK energy future should be 'electrified' (Speirs, et al. 2010) as a suite of low carbon generation technologies provide ever increasing proportions of electricity supply. Life cycle case studies were completed on two technology examples that could make significant contributions to low carbon power supply in the UK. That of industrial CHP and tidal power: the former case study being on an existing natural gas fired CHP plant and the latter being the Severn Barrage scheme as it was proposed until 2010.

The Barrage has undergone carbon and energy assessments in the past, but this study generated the most thorough life cycle inventory to date, and hence the most reliable results. Significantly, the assessment has shown that the operation stage of the Severn Barrage is the largest contributor to the total environmental impact of the plant over its lifetime, whether 'flood pumping' is included in the inventory or not. This finding is in stark contrast to the conclusions of previous studies that have either dismissed (Black & Veatch 2007) (Woollcombe-Adams, Watson and Shaw 2009) or underestimated (Roberts 1982) (Spevack, Jones and Hammond 2011) the operation stage. The large difference can be entirely attributed to the re-estimate of the operational electricity requirement based on demand figures taken from the STPG (Severn Tidal Power Group and the Department of Energy 1989) report.

The CHP case study focused on the consequences of replacing a heat only systems where there is an established heat load, so with this in mind the 'fixed heat' allocation method was developed where only that impact which is over and above the impact which the previous heat only system would have had anyway, is allocated to the power generated. The so-called, DUKES method, which simply splits the allocation between heat and power at a 1:2 ratio was also used for comparison. The specific impact estimates were smallest when the 'fixed heat' method was applied, which serves to demonstrates that the benefit of a scheme CHP rest on appropriate application and confirm the, already generally held, belief that the best performance results are obtained where there is an established heat demand.

The UK Transition Pathways research consortium has generated a set of three low carbon scenarios, together with the corresponding technology mixes at intervals up until 2050 (Foxon, Hammond and Pearson 2010). Uniquely, the consortium has completed carbon focused LCAs, inclusive of upstream emissions (Hammond, Howard and Jones 2013). The results of the Transition Pathways work so far have provided a future context the case study technologies but are also used in the inventories of both case studies. Thus, the impact of the Grid mix itself has been shown to be a variable in the assessment of any individual technology and, consequently, assessment of the Grid is, itself, iterative. In this way, this thesis also showcases the importance of the relationship between focused studies on individual technologies and over arching studies of the full Grid mix. The scenario narratives were also used to explore and understand the interactive relationship that the two studied technologies could have with each other and the National Grid mix on the pathway to 2050.

The Severn Barrage has been shown to win its place in the 2050 low carbon deal even if the National Grid remains at its current carbon intensity, whereas industrial CHP would fall short of the required carbon intensity for the ideal 2050 even if 100% bio-fuelled. It is, however, important to remember, that the targets set for 2050 are an ideal, if the carbon intensity of the National Grid were to, in fact, remain at its current carbon level then even 100% natural gas fired CHP would continue to offer significant relative benefits. Even if the National Grid achieves the low carbon ideal by 2050 it will do it at a pace that decisions to commission new CHP schemes or replace current ones can be done on a rolling basis and the short design life of a CHP means that no more than a 30 year projection would be required. The 30 year lifespan also dictates that units brought on line today, and until 2020, would be decommissioned by 2050 anyway so the fear of 'lock-in' is ungrounded in this respect. Importantly, when the overall environmental impact was considered, the CHP system was shown to outperform the 2050 Transition Pathway Grid mixes in a number of cases. This shows that the pursuit of exceptional improvement in one impact area could lead to the sacrifice of others. Furthermore, to fear technology 'lock-in' in the future more than the consequences of high carbon emissions and environmental impacts today, is surely to underestimate the consequences of those emissions and impacts. Reducing carbon emissions and fossil fuel consumption now *is* essential to stabilizing the climate in time for future generations. A future power Grid free from primary fuelled technology will be little consolation if so-called 'run away' climate change has already been triggered.

This research has shown that one significant development that would reduce the carbon intensity of the National Grid would be the commissioning of the Severn Barrage. If the scheme goes ahead, whenever that is, then it might mark the point at which CHP begins to come at a carbon cost. However because the carbon intensity of power from the Barrage is reliant on that of the National Grid mix, further CHP implementation should only be stopped if there is a suitable low carbon *and* low impact alternative that can fill the capacity gap that would be left. This analysis shows that to fear that today's CHP schemes could represent a technology 'lock-in' in the future enough to prevent further installation is to underestimate the role the technology has in the current and future Grid mix.

The work presented demonstrates the importance of life cycle thinking in the development of a low impact energy strategy. The Severn Barrage study has highlighted the pitfalls of ignoring the operation stage of a renewable scheme, particularly one with a very long lifespan. And further to this, the complex nature of a single scheme that will live through many changes in the supply of inventory resources. The CHP case study demonstrated the importance of considering a range of environmental impacts. The discussion has also shown the importance of scenarios in developing an energy strategy for such an ambitious change. The pursuit of change implies that the future is necessarily dynamic. The work has shown that scenario thinking allows exploration of potential strategy decisions and hence, is essential to having confidence in those decisions.

11.1 FUTURE WORK

As already discussed in Chapter 3, LCA is only one appraisal methodology that should be used in combination with others, particularly social and economic appraisals, to reach a full sustainability assessment. Hence, this research necessarily implies the need for further assessment in different discipline areas. In particular, it has been stated that an assessment of the ecological impacts that follows the comparative approach adopted here, is required. In addition to the further analyses of the specific technologies the following areas of further work have been identified.

11.1.1 FUEL AND MATERIAL IMPLICATIONS OF MASS ROLL OUT

The study also demonstrates that converting from a heat only system to a CHP system will lead to an additional 4 GJ of energy demand from primary fuel per MWh generated. This implies that if an additional 41 TWh(e) were to be generated via CHP conversion, an additional 164 PJ of primary fuel would be consumed in the UK. The case study assumed that natural gas would be supplied from North Sea gas wells and that bio-gas could be provided by purified gas extracted from waste streams. A feasibility assessment would be advisable to determine the likelihood and consequences of meeting the extra demand with either one of these fuels. Alternative sources of natural gas may need to be exploited if demand increases, for instance shale gas, and these are likely to have a different impact profiles. The supply stream of bio-fuels in the UK is still developing so an assessment of its ability to meet demand would be required along with the impact implications of the practices it might displace, for instance composting and recycling.

The carbon implications of installing a number of tidal barrage schemes across viable UK estuaries have been discussed. This is unlikely to happen for a considerable number of years, if ever. However the idea does raise the consideration of the feasibility of providing a sufficient supply of building materials to undertake that level of development, inclusive of the impact variation between national and international feed stocks. An assessment of this nature would set a benchmark against which other widespread development for energy could be compared, e.g. extensive new nuclear power stations or wind farms. After all, to realise the low carbon 'electrified' future a considerable amount of manufacture and construction will be required, no matter what mix of technologies is preferred.

11.1.2 ASSESSMENT OF ALTERNATIVES

Both these technologies have alternative technology options that they should be compared to as choosing either one of these technologies necessarily means closing off the alternative path.

The installation of a barrage in a suitable tidal estuary would render any other tidal range technology development unviable. A number of alternative tidal range schemes have been proposed for the Severn estuary which claim to exploit the energy resource but in a less ecologically intrusive way, although none achieve the level of output that a barrage can. In order to make an informed choice, an assessment that is as robust as this one should be completed on the most realistic alternative schemes

The research has suggested that simply switching from natural gas to bio-gas to fuel a heat only system would generate greater impact savings than converting to a natural gas CHP system. This switch would also not have to wait for the current heat only system to reach end of life as the only change required would be the supply from the national gas grid. The additional fuel demand associated with a switch to CHP from heat only production would put extra stress on the national gas grid and hence may delay or prevent the fuel switch to bio-gas, which may be insufficient. Hence sticking to gas fuelled heat only systems, and investing in incorporating increasingly more bio-methane into national gas supply rather than in site by site infrastructure changes is perhaps the more efficient choice. A feasibility study of bio-gas fuel supply, as suggested above, would be required to determine the validity of this fear but also a relative assessment of the life cycle impact savings of the infrastructural development avoided against those lost via the lack of low power generated should be carried out.

11.1.3 WHAT IS ‘NORMAL’?

Although there are strong arguments for only using characterised impact results, as discussed in Chapter 3, normalised results are often preferred as they are a much more penetrable way of explaining conclusions to a varied audience. Characterised results are always given in this thesis but normalized results and even the total normalised impact scores are also used consistently. Normalising a result against a reference system necessarily ties that result to the temporal and geographical constraints of that system. Hence the attempts of this work to put the LCA results in the context of a dynamic pathway stretching into the future are limited whenever a normalized impact result is used. In order to use normalised results more effectively, a range of reference systems should be used that include future scenarios. This presents a challenge for the LCA community at large, particularly in the development of a LCSA methodology, as discussed in Chapter 3.

11.2 SUMMARY OF ORIGINAL CONTRIBUTION

In meeting objective (a):

The focus on under exploited technologies and their roles in the future is itself an uncommon approach. Studies have been completed on the technology types in isolation but have not considered their potential role in the future energy mix.

In meeting objective (b):

The robust application of the LCA method to the two selected technologies, rather than restricting the accounting to basic ‘on site’ impacts, is adding a much needed and often over looked complexity to the problem. Furthermore, the thorough life cycle inventories and results interpretations generated could be used as a benchmark to assess other energy systems as well as to continue investigation into either one of the specific technologies.

The additional comparisons made in this work to potential future Grid mixes are an important step to providing a full assessment of the benefits available. Previous analyses of low carbon generators have tended to judge the impact savings in comparison to the current National Grid or a single ‘conventional’ power generator. The comparisons made with future Grids are, by definition, speculative but it is essential that potential future scenarios and technology changes are analyzed and speculated upon in order to develop an informed energy strategy to meet the environmental targets set.

The improvements made to the inventory data set provided by previous studies showed that the operation stage of Severn Barrage was by far the most impactful, a finding that had so far been overlooked. This leads to the clear recommendation that ‘flood pumping’ should not be included in the Severn Barrage design. This also demonstrates that the operational impact of even a renewable technology should not be taken for granted, particularly for a scheme with a very long lifespan. It shows that where there is an operational electricity demand, the impact intensity of the Grid mix taken to meet the demand is critical to the overall impact of the system. Therefore, when such schemes are analysed it is crucial that they are not done so in isolation, but in conjunction with a wider knowledge of any associated power inputs to the system.

Comparisons drawn between the environmental impacts of the CHP unit and that of the future low carbon Grid mixes have shown that even bio-gas CHP cannot make a direct contribution to meeting the 2050 carbon reduction target but, in most cases, it would have a lower overall environmental impact than the low carbon National Grid mix in 2050, as suggested by the Transition Pathways scenarios. This draws much needed attention to the fact that optimising the Grid mix for low carbon generation should not risk higher impacts in other areas of environmental concern nor the rejection of a technology that has a good overall environmental impact performance.

In meeting objective (c) and (d):

The exploration of the interactions that the studied technologies might have with each other and with an evolving Grid mix in the future is unique. This discussion hopes to set a precedent that strategy decisions must be made with a wider appreciation of the dynamic roles that a given technology can have towards overall sustainability, rather than based solely on a static quantification of the specific carbon savings they achieve.

11.3 OVERALL CONCLUDING RECOMMENDATIONS

- The decision to implement of any low carbon energy system should be made relative to the specific impact of the Grid.
- If the Severn Barrage is commissioned, it should operate in ebb generation mode only. The power generation benefits gained from 'flood pumping' are outweighed by the additional energy demand from the Grid and far outweighed by the associated environmental impact.
- Widespread implementation of industrial CHP can make a significant impact on carbon reduction now and should be implemented as soon as possible to maximise this benefit. Although, future CHP implementation and the replacement of decommissioned units should be re-assessed relative to the specific impact of the contemporary Grid mix, especially if the Severn Barrage or similar scale renewable scheme has been implemented. Decarbonisation based on widespread implementation of CCS technology should not prevent the implementation of industrial CHP as this would lead to the exacerbation of other environmental impacts, particularly fossil fuel depletion.
- Prioritising carbon benefit should not lead to the marginalisation of every other performance indicator as this would exacerbate other environmental issues. Carbon intensity is likely to remain the focus of technology assessments as we approach 2050 because of the reduction targets set but the work has highlighted the importance of other environmental impacts and that at least fossil fuel depletion should be included in future comparative assessments.
- The operation stage of any renewable energy system should not be automatically ignored, particularly a scheme with a very long design life.
- The ecological impacts of constructing the Severn Barrage should be assessed in comparison with those of the power supply that would have to be provided by the National Grid in the absence of the Barrage.
- A practical feasibility assessment of construction material provision and fuel feed stocks is required for both these technologies.
- In light of a completed bio-gas feedstock feasibility study, the benefits of bio-gas fuelled heat only systems should be assessed as a solution to reducing the impact of industrial heat demand.

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APPENDIX A. FURTHER BACKGROUND ON TRANSITION PATHWAYS RESEARCH CONSORTIUM WORK

The consortium project ‘Transition Pathways to a Low Carbon Economy’, made up of researchers from nine UK Universities, is intended to answer these questions. It proposes to,

> “*...undertake socially and scientifically engaged research into innovative technologies, policies and practices leading towards a low carbon energy system*” (Transition Pathways Consortium Team n.d.).

When planning for meeting these ambitious targets, the following questions arise:

1. How will the socio-economic landscape develop in the UK up to 2050 within the context of this legislation and what implications will this have on the supply and demand of energy?
2. Which low carbon energy generating technologies can feasibly be employed to supply the UK electricity network and in what proportions will they be needed to meet the demand predicted in the possible socio-economic futures?
3. Will these potential technology mixes meet the UK carbon reduction targets?
4. What are the wider environmental consequences of the low carbon technologies proposed?

The project approach adopted can be broken down to the following steps:

1. Define the question. Can we combine social and techno-economic ‘insights’/lessons from the past?
2. Define the system. Characterise the existing energy regime in terms of ‘landscape pressures’ and ‘internal tensions’.
3. Describe how the system is predicted to evolve. Three Scenario story lines have been produced:
   - Central Control: The government is the main actor.
   - Market Rules: Industry is the main actor.
   - Thousand Flowers: Consumers/citizens are the main actors.
4. Appraise the prediction. In terms of:
   - Robustness: what are the ‘branching points’? How easily can a scenario be ‘derailed’?
   - Feasibility: are the socio-technological changes required realistic?
   - Total Environmental Impact: do the scenarios meet the emission targets? With or without accounting for ‘upstream’ emissions? What are the other related impacts?

The consortium work splits into 3 themes:

1. Transitions, Scenarios and Historical Analysis
2. Technical and Social Analysis
3. Whole System Appraisal

The research completed for this individual PhD project is intended to contribute to Theme 3, Whole System Appraisal.

WHOLE SYSTEM APPRAISAL

The work completed for this thesis is intended to contribute to theme 3, *Whole System Appraisal*, of the Transition Pathways project. According to the principal investigator of theme 3,

> "…*'whole systems appraisal' normally implies technical, energy, environmental and economic evaluations*…" (G. P. Hammond 2012).

Figure 87 visualises the relationship between the different assessments required to carry out a 'whole system appraisal' and shows that LCA should really be seen as providing one tool among a tool kit. It should be noted that a whole system appraisal is *not* a sustainability assessment as it does not include any social analysis. Environmental LCA can from one element of both a 'whole system appraisal' and a LCSA, as described in 2.5.2, but a 'whole system appraisal' could also be part of a wider sustainability assessment.

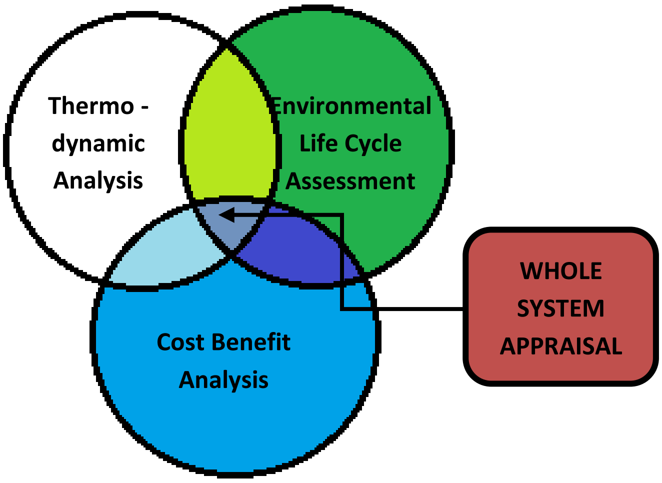

Figure 87 Relationship between analyses undertaken as part of a whole systems appraisal

According to the project, Theme 3 will propose answers to the questions of:

1. Will potential technology mixes meet the UK carbon reduction targets?
2. What are the wider environmental consequences of the low carbon technologies proposed?

With respect to question 1, the capacity of the LCA approach to include up and down stream impacts, regardless of time and space, is precisely what lends the work carried out by the Transition Pathways team the unique edge over previously commissioned and/or completed scenario projects. As the UK strives to meet its carbon reduction targets it is all too easy to forget that environmental stability and sustainability is a planet wide priority and we should not restrict the carbon calculations to only what happens on this island up until 2050. This has been the fault in many carbon foot printing scenario studies so far.

With respect to question 2, this also partly addressed by adopting the LCA approach as, already described, LCA was founded on the desire to account for a suite of environmental impacts across a products whole lifetime. And, again this is often omitted from other purely carbon focused studies which risks ignoring other environmental sacrifices made for the benefit of carbon reduction.

APPENDIX B. FURTHER DETAIL ON IMPACT CATEGORIES

RECIPE IMPACT CATEGORIES

The following extract is taken from the SimaPro Methods Manual (Goedkoop, Oele, et al. 2010, 19-20) in order to provide some extra explanation of the impact categories used in the environmental assessments.

Ozone depletion	*The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). The unit is yr/kg CFC-11 equivalents.*
Human toxicity and ecotoxicity	*The characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. The unit is yr/kg 1,4-dichlorobenzeen (14DCB).*
Radiation	*The characterization factor of ionizing radiation accounts for the level of exposure. The unit is yr/kg Uranium 235 equivalents.*
Photochemical oxidant formation	*The characterization factor of photochemical oxidant formation is defined as the marginal change in the 24h-average European concentration of ozone (dCO3 in kg·m−3) due to a marginal change in emission of substance x (dMx in kg·year−1). The unit is yr/kg NMVOC.*
Particulate matter formation	*The characterization factor of particulate matter formation is the intake fraction of PM10. The unit is yr/kg PM10 equivalents.*
Climate change	*The characterization factor of climate change is the global warming potential. The unit is yr/kg CO_2 equivalents.*
Agricultural and urban land occupation	*The amount of either agricultural land or urban land occupied for a certain time. The unit is m2*yr.*
Natural land transformation	*The amount of natural land transformed and occupied for a certain time. The unit is m2*yr.*
Marine eutrophication	*The characterization factor of marine eutrophication accounts for the environmental persistence (fate) of the emission of N containing nutrients. The unit is y/kg N to freshwater equivalents.*
Freshwater eutrophication	*The characterization factor of freshwater eutrophication accounts for the environmental persistence (fate) of the emission of P containing nutrients. The unit is yr/kg P to freshwater equivalents.*
Fossil fuel and minerals depletion	*The characterization factor of fossil depletion is the amount of extracted fossil fuel extracted, based on the upper heating value. The unit is MJ.*
Minerals depletion	*The characterization factor for minerals depletion is the decrease in grade. The unit is kg Iron (Fe) equivalents.*
Freshwater depletion	*The factor for the freshwater depletion is the amount of fresh water consumption. The unit is m3.*

CUMULATIVE ENERGY DEMAND CATEGORIES

The following extract is taken from the EcoInvent report, '*Implementation of Life Cycle Impact Assessment Methods*' (Frischknecht and Jungbluth 2003, 32. Table 2-2)in order to provide some extra explanation of the impact categories used in the energy assessments.

	Subcategory	***Includes***
Non-renewable resources	***Fossil***	*hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat*
	Nuclear	*uranium*
	Biomass	*wood and biomass from primary forests*
Renewable resources	***Biomass***	*wood, food products, biomass from agriculture, e.g. straw*
	Wind	*wind energy*
	Solar	*solar energy (used for heat & electricity),*
	Geothermal	*geothermal energy (shallow: 100-300m)*
	Water	*run-of-river hydro power, reservoir hydro power*